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Established in 1818 by Benjamin Silliman

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Lane, R. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

[American Journal of Science, Vol. 249, September, 1951, Pp. 625-639]

American Journal of Science

SEPTEMBER 1951

SOME ASPECTS OF ROCK FOLDING BY SHEARING DEFORMATION

J. D. CAMPBELL

ABSTRACT. Some published experimental work suggests that a stress condition, additional to those usually recognized, can develop within a bed during folding and give rise to a set of cleavage planes parallel to the bed surfaces. Although not proved experimentally, it is possible that the complementary shear could develop, giving shearing at right angles to bedding instead of parallel to it.

A fold formed by slipping on a large number of cleavage planes parallel to the bed surfaces gives rise to a concentric fold. Slipping on cleavages which originally were at right angles to bedding, leads to the development of a similar fold.

Other experiments suggest that a folded mass could be foreshortened in much the same way that a thick slab of clay can be squeezed up by a compressive stress. If such a process is applied to a previously formed similar fold, the fold retains its similar character but is considerably increased in strength for a relatively small foreshortening. The foreshortening of a concentric fold causes it to assume some of the characteristics of a similar fold: the greater the foreshortening the more the resemblance to a similar fold.

Combining some of the features of each of the two processes suggested above gives an explanation of the formation of cleavage in the less competent members of a mixed series of sediments (*i.e.* slates and sandstones), and suggests that the development of these cleavage planes and slipping on them are the key to the formation of a similar fold.

INTRODUCTION

IN this paper a series of idealised folds is examined. The mechanisms by which they are assumed to form would probably have little direct application to the fold problems usually encountered in field work. Nevertheless, it is believed by the writer that they offer clues which can be helpful in the analysis of more complex fold forms.

To develop these ideal folds several assumptions are needed. The main assumption in each analysis is that stress relief is solely by means of a particular form of strain. The purpose is to reach clear conclusions on the relationships between

the geometric properties of folds and particular types of shearing deformation by which they could be formed.

Other assumptions are:

1. That the volume of a unit block of rock is not altered by a shearing deformation.
2. That, during deformation, there is no change in dimension along the axis of mean strain.

These two latter assumptions are made to allow the use of two-dimensional illustrations and to introduce a quantitative element into the analysis of the diagrams.

Dimensional relationships based on these assumptions are given in figure 1.

EXPERIMENTAL WORK OF KUENEN AND DE SITTER

Kuenen and de Sitter (1938) conducted a series of experiments which was designed to study the deformation occurring within a folded bed rather than the interplay of stresses between the members of a series of beds. A test for strength and plasticity was devised which allowed the repetition of experiments on test pieces of similar characteristics.

One set of experiments used slabs of modelling clay which were plastic but showed a small degree of strength. A single slab of clay was subjected to a compression, and it was found that, although the material was entirely unstratified, curved shear planes were developed which were parallel to the surfaces of the test piece. The shears showed reversed fault movements (Kuenen and de Sitter, 1938, fig. 15, p. 235). These experimental results are sketched in figure 2 and the internal stress condition necessary to produce them is suggested in figure 3a.

The critical factors determining the occurrence of this phenomenon must be the thickness of the bed and the radius of curvature to which it is bent, in relation to the strength and elasticity of the material of which it is composed. It is evident that, for a given material and a given radius of curvature, there is a critical thickness for a bed and that, if this thickness is exceeded, the bed will split up into units which are equal to or somewhat smaller than the critical size.

Within each of the smaller units so produced, the decreasing

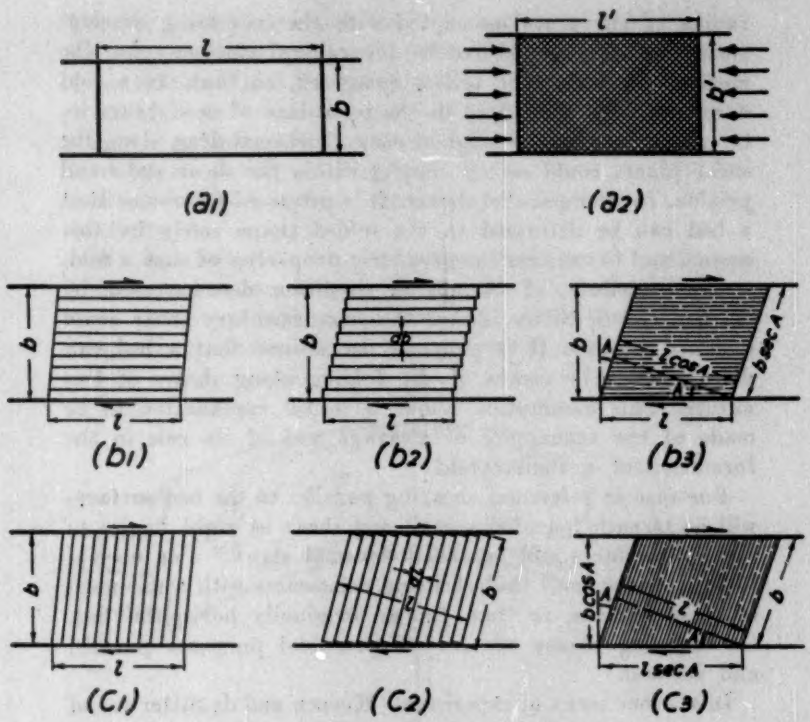

Fig. 1. Dimensional relationships in shear deformation.

(a) Deformation by pure shear.

After deformation (a2) $b' = b \times \frac{l}{l'}$ or $l' = l \times \frac{b}{b'}$.

(b) Deformation by simple shear parallel to bedding.

(b1) = limited number of potential shear planes at point of elastic limit.

(b2) = same after rupture.
Bed thickness = Σ (db) is not changed by the deformation.

(b3) = same for closely spaced shears.
As dimensions b and l are unchanged, the thickness of the bed and its length will remain unaltered no matter how far the deformation progresses.

(c) Deformation by simple shear originally normal to bedding.

(c1) = elastic limit.

(c2) = deformation by a limited number of shearing planes. Dimension l, measuring at right angles to shearing, = Σ (dl) and is unchanged.

(c3) = same for closely spaced shears.
If A = angle of deformation, the bed thickness is reduced to b cos A and its length is increased to l sec A.

radius of curvature associated with the increasing development of a fold would reduce the critical thickness for the material of which the bed is composed, so that, as a fold developed, this could lead to the formation of new shears interspaced between the original ones. Frictional drag along the shear planes could set up couples within the shear slabs and produce further parallel shears. It is proposed to assume that a bed can be deformed to the folded shape solely by this means, and to examine the geometric properties of such a fold.

The corollary of the stress condition demonstrated by Kuenen and de Sitter is that the complementary shear could develop (fig. 4). It is proposed to assume that a bed can deform solely by means of slip folding along shears of this nature. This assumption allows a useful explanation to be made of the occurrence of cleavage and of its role in the formation of a similar fold.

For ease in reference, shearing parallel to the bed surfaces will be termed "parallel shear" and shear at right angles to the bed surfaces will be called "normal shear." For normal shear, it is assumed that shearing commences with a minimum of elastic strain, so that, for an originally horizontal bed, the shearing planes are for all practical purposes parallel and vertical.

In another series of experiments Kuenen and de Sitter found

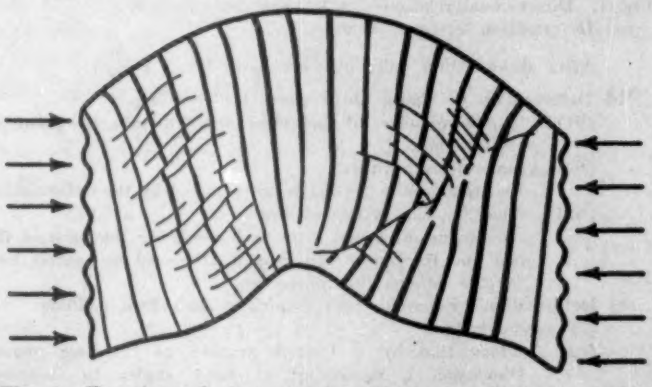

Fig. 2. Experimental demonstration of shear parallel to bedding. Kuenen's and de Sitter's Experiment No. 74, using unstratified plastic clay 4 cm. thick. The more or less vertical lines are markers used to indicate shearing movements.

that, for truly plastic material, the reaction of the test-piece was related to the rate of application of the compressive stress (Kuenen and de Sitter, 1938, fig. 4, p. 222; fig. 5, p. 223). If the stress was applied very slowly, a slab was merely shortened and correspondingly thickened without the development of any folding, but, if the stress was applied rapidly, folding was found to develop in material of similar plasticity.

In a naturally occurring fold which is approaching closure, it must become increasingly difficult for the beds to achieve stress relief by folding, *i.e.* the rate of deformation must progressively decline. For a given material, a point could be

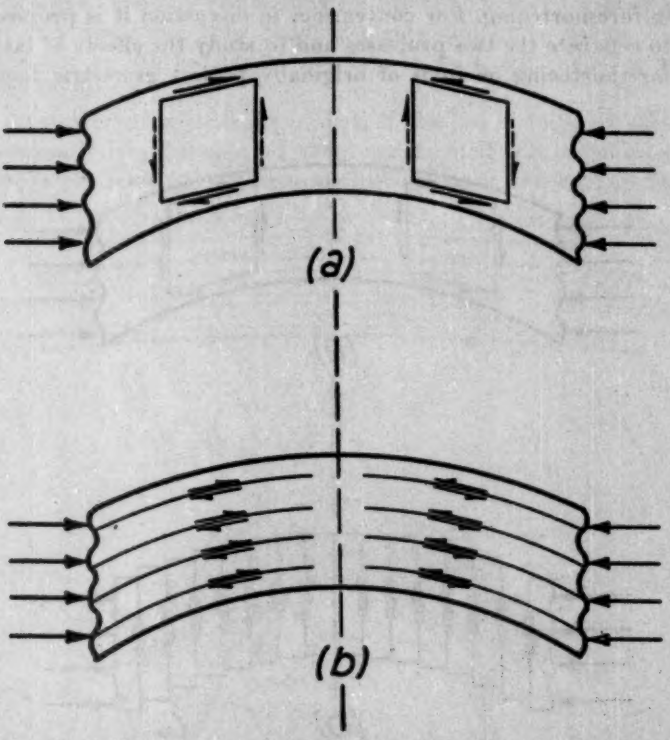

Fig. 3. The internal stress condition suggested by the experimental result shown in figure 2.

The full arrows indicate the active couples (fig. 3a). The inoperative complementary couples are shown in dashed arrows. Shearing planes and movements are indicated in figure 3b.

reached therefore, where the preferred method of deformation is by shortening and thickening of the already folded mass rather than by a continuation of relief by folding. In the Burbanks mine at Coolgardie, Western Australia, pillows in steeply dipping lavas, occurring at the crest of an anticline, are commonly only a few inches thick at right angles to bedding and many feet long in the direction of dip. These proportions are quite different from the more ovoid pillows usually found in the district and are thought by the writer to indicate extreme squeezing of the beds.

If the process suggested here operates in nature it would be reasonable to expect a gradual changeover from folding to foreshortening. For convenience in discussion it is proposed to separate the two processes and to study the effects of later foreshortening on folds of originally perfect geometric form.

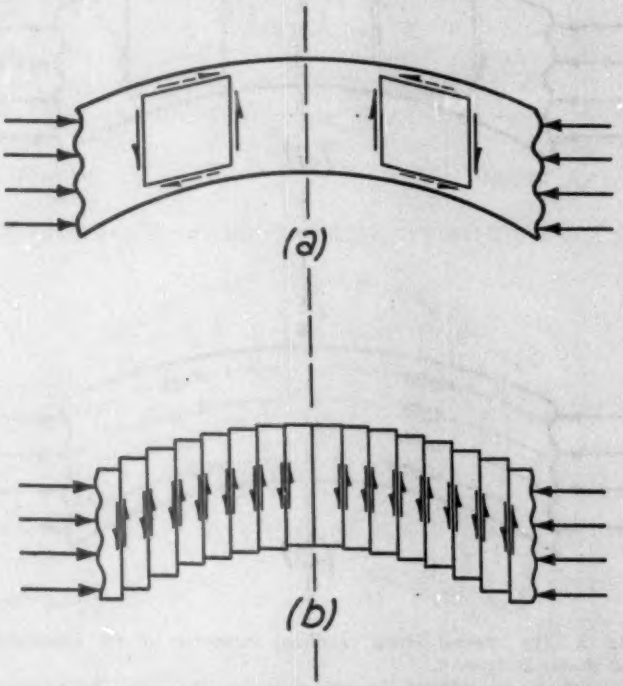

Fig. 4. The complementary shears (full arrows) are regarded as the active couples in figure 4a, giving rise to the fracturing shown in figure 4b.

FOLDING BY CLEAVAGE SLIP

Concentric Folding.—It is evident from figure 1 (b3) that, if a bed is deformed solely by parallel shear under the ideal conditions which have been assumed, its thickness will remain unchanged no matter how far the deformation progresses. If, therefore, a bed achieves a folded shape by parallel shear, as in figure 5, its thickness at all points in the fold limbs will be the same as it is at the axial plane, *i.e.* a concentric fold will form.

It is suggested that this process would find its greatest application where sedimentation has given a bed a grain parallel to bedding and a predisposition, therefore to shearing in this direction. True bedding planes cannot be taken into account as the bed would not behave as a unit under such conditions.

An interesting sidelight is that, if the bed is fully adjusted internally, slip between adjacent points in it will be on a microscopic scale only. The same will apply at the contacts of

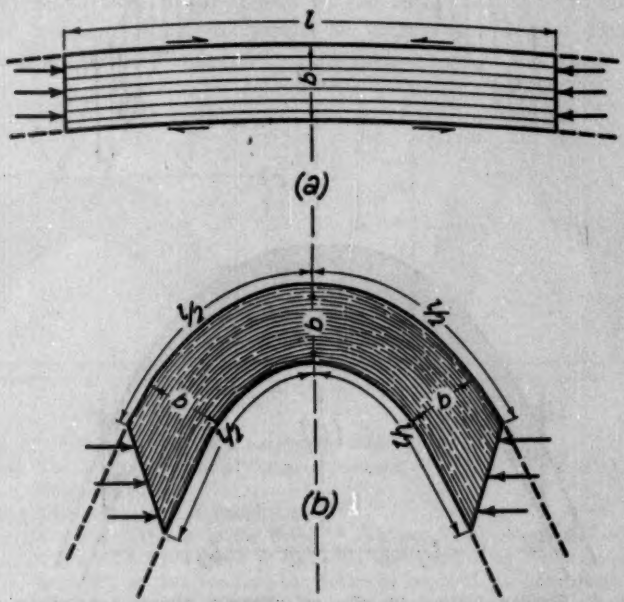

Fig. 5. Concentric folding by slip on cleavage planes parallel to bedding.

the bed with its neighbours above and below, *i.e.*, there will be virtually no slipping between adjacent beds during folding.

Similar Folding.—In figure 6 the deformation of a bed solely by shear normal to bedding is considered. The process is, of course, the well known phenomenon of slip folding.

For purposes of analysis the slabs are shown as being of

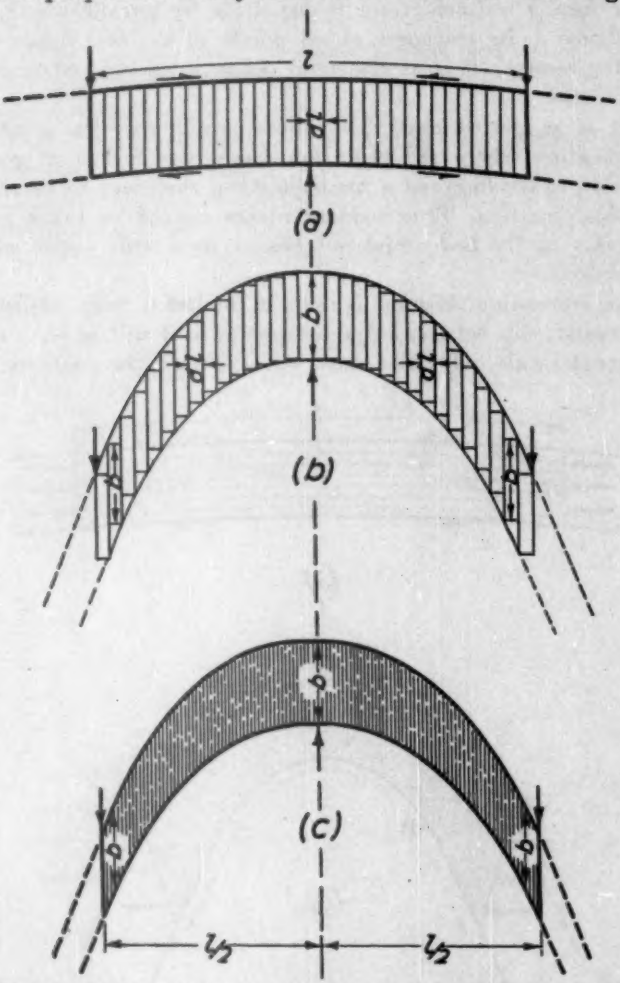

Fig. 6. Similar folding by slip on cleavage planes parallel to the axial plane.

finite thickness in figure 6b and it can be seen that, as the dimensions of the individual slabs are assumed to be unaltered by the deformation, the length of the shear slabs will always be equal to the original thickness of the bed, in the limbs of the fold as well as at the crest. The distance between the upper and lower surfaces of the bed, measured parallel to the axial plane (fig. 6c) will thus be the same in all parts of the fold; hence the two surfaces of the bed will be of the same shape, and the fold produced will be of the similar type.

By reference to figure 6b, it can be seen that, as the width of the slabs is unaltered by the deformation, the sum of the slab widths (measuring at right angles to the shearing direction) is equal to the undeformed length of the section of the bed under consideration. It is apparent, therefore, that there can be no shortening of the bed during folding and that, in its ideal form, this type of folding can be developed only by a bending stress. It is evident, of course, that the slip on the cleavage planes must be actuated by a vertically acting force. Deformation is achieved not by shortening the beds but by stretching them, chiefly in the fold limbs. For a 60° dip of bedding the limbs would be increased to twice their original length and reduced to half their original thickness.

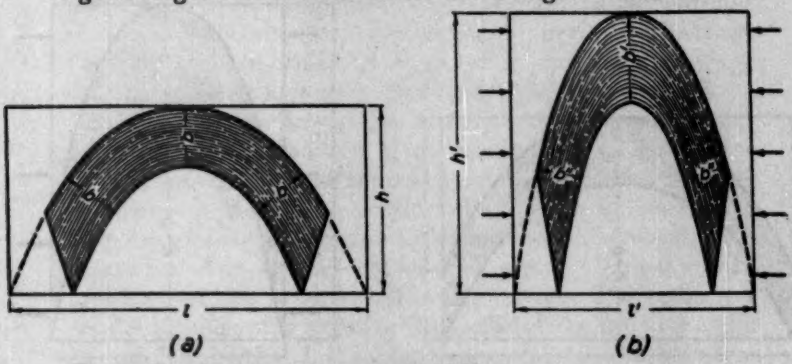

Fig. 7. Foreshortening of a concentric fold.

(a) The concentric fold of figure 5 enclosed in a hypothetical block of dimensions l x h.

(b) The same after deformation.

The bed thickness in the limbs b″ has been reduced and the thickness at the axial plane b′ has been increased, b′ is approximately twice b″, so that the fold has taken on some of the characteristics of a similar fold. Additional foreshortening would further reduce b″ and increase b′, thus increasing the tendency to "similarity."

FORESHORTENING OF FOLDS

Concentric Fold.—The concentric fold of figure 5 is reproduced in figure 7a and foreshortening of it by pure shear is considered. For purposes of analysis the fold is enclosed within a unit block of dimensions $h \times l$. If the compression is uniform, this block, and with it the fold, will be shortened to a length of l' and its height will be proportionately increased to h', where $\frac{h'}{h} = \frac{l}{l'}$.

If the strength of the fold is measured by the ratio $\frac{h}{l}$ (fig. 7a), it can be shown by a simple calculation that its strength after the deformation $\left(\frac{h'}{l'}\right)$ has been increased in the proportion $1 : \left(\frac{l}{l'}\right)^2$. In figure 7b the fold has been foreshortened by one-third; the fold strength has been increased by $\left(\frac{3}{2}\right)^2$, *i.e.* it has been more than doubled.

It is noticeable in figure 7b that the deformation has led to a thinning of the fold limb and a corresponding thickening

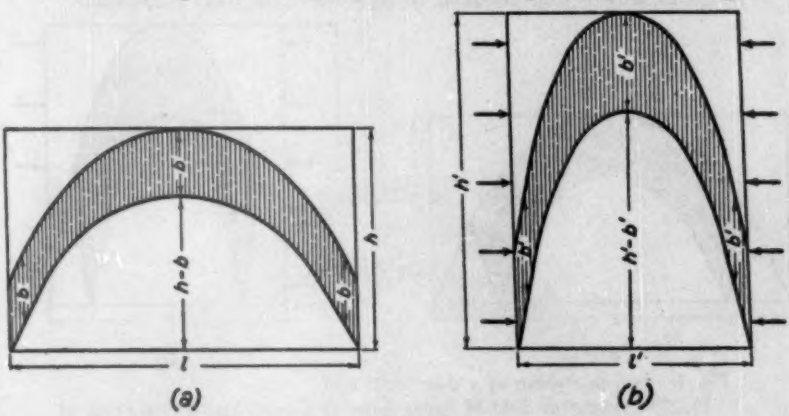

Fig. 8. Foreshortening of a similar fold.

(a) The similar fold of figure 6 enclosed in a hypothetical block of dimensions l x h.

(b) The same after deformation.
The dimension b' is increased to the same degree in the fold limbs as at the fold axis. The lower surface of the bed preserves therefore a shape similar to that of the upper surface.

at the anticline. This has caused the original concentric fold to take on some of the characteristics of a similar fold: further foreshortening would increase the resemblance to a similar fold.

Similar Fold.—In figure 8 a similar analysis is applied to the similar fold of figure 6.

In this case the dimension b of figure 6 is increased in the ratio $\frac{l}{l'}$ in the fold limbs as well as at the crest of the anticline. The altered dimension b' in figure 8b will be the same at all points of the fold and a "similar" form will be preserved therefore.

As with the concentric fold, the strength of the foreshortened fold is proportional to the square of the reciprocal of the ratio of foreshortening.

SIMILAR FOLDING IN MIXED SEDIMENTS

Figure 9 shows three beds which are subjected to a compressive stress. The upper and lower beds are competent, say sandstone, and the middle bed is incompetent, say shale. The two competent beds form concentric folds of identical shape, the necessary adjustments being made by the incompetent bed. The incompetent bed is assumed to be deformed by slip on fractures which were originally normal to bedding. The slip is accompanied by a squeezing up of the cleavage slabs to degrees which vary in different parts of the fold.

In figure 9b the early stages of deformation and fracturing are suggested and two unit blocks are indicated, no. 1 at the axial plane and no. 2 in the middle of the fold limb. The deformation of block 1 is considered in figure 9c where, for purposes of analysis, the two types of reaction are considered separately. The stresses on block 1 are the primary compression and the secondary shearing couples. The secondary couples are regarded as being the result of the bending of the incompetent bed, and the clockwise couple is considered as being the active one (refer righthand half of fig. 4a). Slip deformation due to it is indicated in figure 9(c1). Deformation, due to the primary compression, is shown in figure 9(c2), where the cleavage slabs are thinned by pure shear in the horizontal dimension and correspondingly lengthened vertically. The combined effect of the two deformations, for closely spaced shears, is indicated in figure 9(c3).

Figures 9d(1-3) give the corresponding stages of deformation for block 2.

The incompetent bed can conform to the shape required by the competent beds above and below it if there is a proper balance at all points in the fold between slip on the cleavage planes and squeezing up of the individual cleavage slabs. Thus (fig. 9e) block 1 is required to show a minimum of slip on the cleavage planes and a maximum of deformation by pure shear. On the other hand block 2 shows only slight alteration by squeezing in its horizontal and vertical dimensions, but a considerable deformation by slip on the cleavage planes (see also fig. 9 (c3) and (d3).

The formation of such a fold requires that the competent beds should slip over the incompetent, to the amounts indicated by the offsetting of the ends of the beds in figure 9e. The

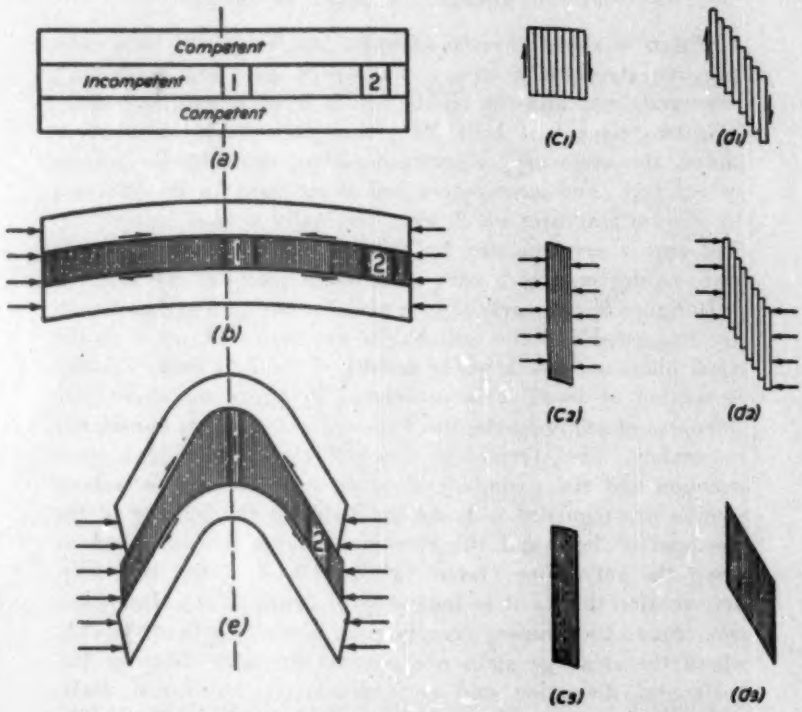

Fig. 9. Formation of a similar fold in series made up of alternating competent and incompetent beds.

perfect fold could form only if there is no friction at these contacts.

Hills and Thomas (1944) have given some data on the deformation of slates in a similarly folded sandstone and slate series. They compared the deformed dimensions of graptolites from the crests of anticlines and from the fold limbs with the known dimensions of undeformed graptolites: they found that at the crests the graptolites (and their enclosing slates) had been shortened to 0.5 of their usual length, and in the fold limbs their length was, if anything, slightly increased. In figure 9 the shortening at the fold axes is in the ratio of 0.45 to 1, and the lengthening in the fold limbs (measuring parallel to bedding) is in the ratio of 1.5 to 1. These deformations are substantially similar to those observed by Hills and Thomas.

In figure 10 foreshortening of all three beds of figure 9e is indicated. This figure shows, in a slightly exaggerated form, a considerable resemblance to the folding seen at Bendigo, where the sandstones show some degree of thickening at the axial planes and a certain amount of thinning in the fold limbs. The marked thinning in figure 10 of the incompetent bed in the limbs and thickening at the fold axis is also substantially similar to the behaviour of slate beds at Bendigo.

CONCLUSIONS

The main purpose has been to offer an explanation of cleavage and to suggest its role in the formation of similar folding. The stress condition suggested by the experiments of Kuenen and de Sitter (fig. 3a) seems sound and, if this is so, the inferred stress condition given in figure 4a is at least possible. The test is the extent to which an explanation can be offered for observed phenomena.

The postulate, often made, that cleavage results from drag stresses set up by one bed slipping over another during folding, has the weakness that there is virtually no slip between beds in the vicinity of the axial planes. Yet, in areas where cleavage is well developed, such as in the Ordovician slates and sandstones of Victoria, there is strong cleavage right through the axial plane areas. The explanation offered here suggests that, under suitable conditions of strength and elasticity of material, the development of cleavage at right angles

to bedding could be the first and main result of the bending of a bed to a folded shape. If this is so, the axial plane portion is the most stressed area and it is therefore the one in which the occurrence of cleavage planes (in number, as distinct from the amount of movement on individual fractures) is at a maximum.

The similar fold which is solely the result of slip-folding, is probably no more than an interesting exercise in the construction of a diagram. If one seeks to apply the mechanism to field problems, the weakness is that, from the outset, a vertically acting force is required. There is no reason to suppose that such a condition would normally exist. The mechanism postulated for the development of a similar fold in a mixed series of sediments does not have this weakness, as the fold is the result of a compressive stress.

The experimental evidence is that foreshortening has been demonstrated in a plastic material and that deformation by the development of finite shearing planes occurs in material

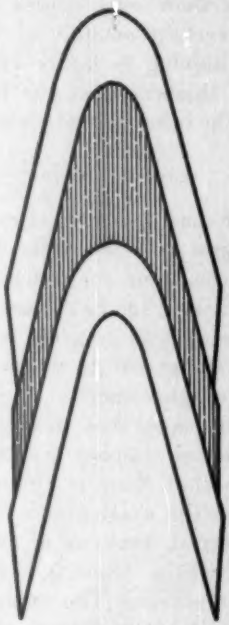

Fig. 10. Foreshortening by pure shear of the fold shown in figure 9e.

which approaches a plastic condition but has some definite strength. The mechanism suggested here for the formation of a similar fold in mixed sediments requires that both fracturing and foreshortening should occur in the one rock (the shale). To some extent the two requirements seem incompatible. The answer may be that both phenomena occur under natural conditions in varying degrees over a wide range of depths and there is thus a considerable zone of overlap in which the processes can occur concurrently.

It is of interest that the foreshortening of a concentric fold causes it to take on some of the characteristics of a similar fold. It is evident that, the greater the foreshortening, cally. The ultimate shape of the deformed block, for closely the more the resemblance to a similar fold. If folds are to preserve their form to any depth, a considerable degree of similarity in the shape of successive beds is required.

In the Precambrian greenstones of Western Australia it is evident from the nature of the structures that the rocks have tended to plastic behaviour during folding. Kuenen and de Sitter have demonstrated that, if a plastic material is deformed rapidly, the tendency is to form a concentric fold. It is apparent in surface mapping in Western Australia, and particularly in the three-dimensional interpretation of mining fields, that the fold structures are predominantly similar in character. The connecting link could be the foreshortening of folds. It may be that deeply buried rocks are deformed initially by concentric folding but, when these folds are approaching closure, the preferred method of deformation then becomes a squeezing up of the already folded mass by pure shear. If the extreme squeezing of pillow lavas at Burbanks (cited earlier) is an indication of the degree of foreshortening which can occur, any original concentric features in the folding would be largely obliterated by the tendency of foreshortening to favour the similar shape.

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Western Mining Corporation, Ltd.
Kalgoorlie, Western Australia

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A FOLDED OVERTHRUST AND ITS EFFECT UPON STREAM DEVELOPMENT IN CENTRAL VIRGINIA*

ROBERT O. BLOOMER

ABSTRACT. Sallings Ridge is the topographic expression of a mass of Lower Cambrian Erwin quartzite in a lobe of an overthrust near the southeastern edge of the Valley and Ridge province. The quartzite is in a symmetrical anticline that has been thrust upon an overturned anticline in the Lower and Middle Cambrian Rome formation. The overthrust surface that separates the allochthonous anticline from the autochthonous anticline is in the form of a syncline. Southeast of this syncline, toward the root zone, there are other folds in the surface of the fault.

All of the bedrock in the Sallings Ridge area is Cambrian or older and the deformation is post-Cambrian. Consequently, there are no stratigraphic data by which the ages of the folds and faults can be determined.

James River has eroded a valley through the allochthonous block so that the present course is "superposed" upon the autochthonous block.

INTRODUCTION

SALLINGS Ridge is an outlier of the Blue Ridge with structural relations that reveal two stages of folding and an intervening stage during which a large overthrust was formed. Differential erosion among the outcrop belts in this area of complex structure has had an important influence upon the development of James River.

Butts (1933) interpreted the structure of Sallings Ridge as an anticline of Lower Cambrian quartzite. Stose and others (1919, plate 3) mapped the structure as an anticline of Lower Cambrian quartzite with a minor thrust fault along the northwest limb. Field studies of the area have shown that Sallings Ridge is almost a klippe joined to the main mass of an overthrust block in the Blue Ridge by a narrow "isthmus".

LOCATION

Sallings Ridge is in the Valley and Ridge province. It is located in Rockbridge County about 3 miles northeast of Natural Bridge and 11 miles southwest of Buena Vista, Virginia (fig. 1). Glasgow is located in the valley between Sallings Ridge and the western end of James River gorge through the Blue Ridge (fig. 2).

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TOPOGRAPHY

Sallings Ridge, as shown in the west-central rectangle of the Buena Vista quadrangle, is about 6 miles long and consists of three well defined summits separated by gaps (fig. 2). On the topographic map these summits from southwest to northeast are named Sallings Mountain, Miller Mountain, and Brady Hill. The name Sallings Ridge is herein used as an expedient where reference to the whole feature is made and has no status as a geographical name.

The Sallings Mountain portion of Sallings Ridge is a narrow, even-crested ridge with a maximum altitude of 1793 feet. Miller Mountain and Brady Hill, on the other hand, are more or less domal hills that have maximum altitudes respectively of 1690 feet and 1515 feet.

Sallings Gap is a wind gap between Sallings Mountain and Miller Mountain (plate 2, fig. 1). At its lowest point, this gap is at an altitude of about 1125 feet which is about 125

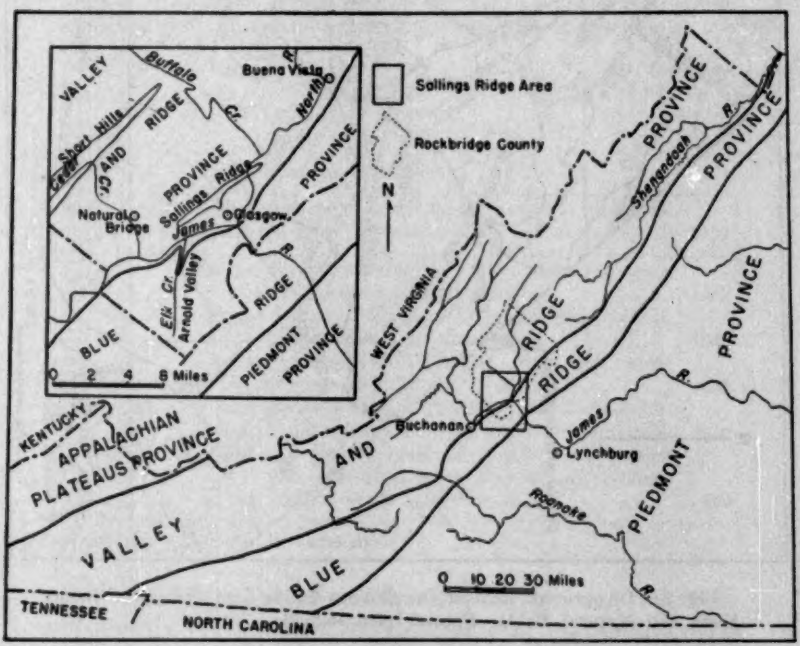

Fig. 1. Index map of the Sallings Ridge area.

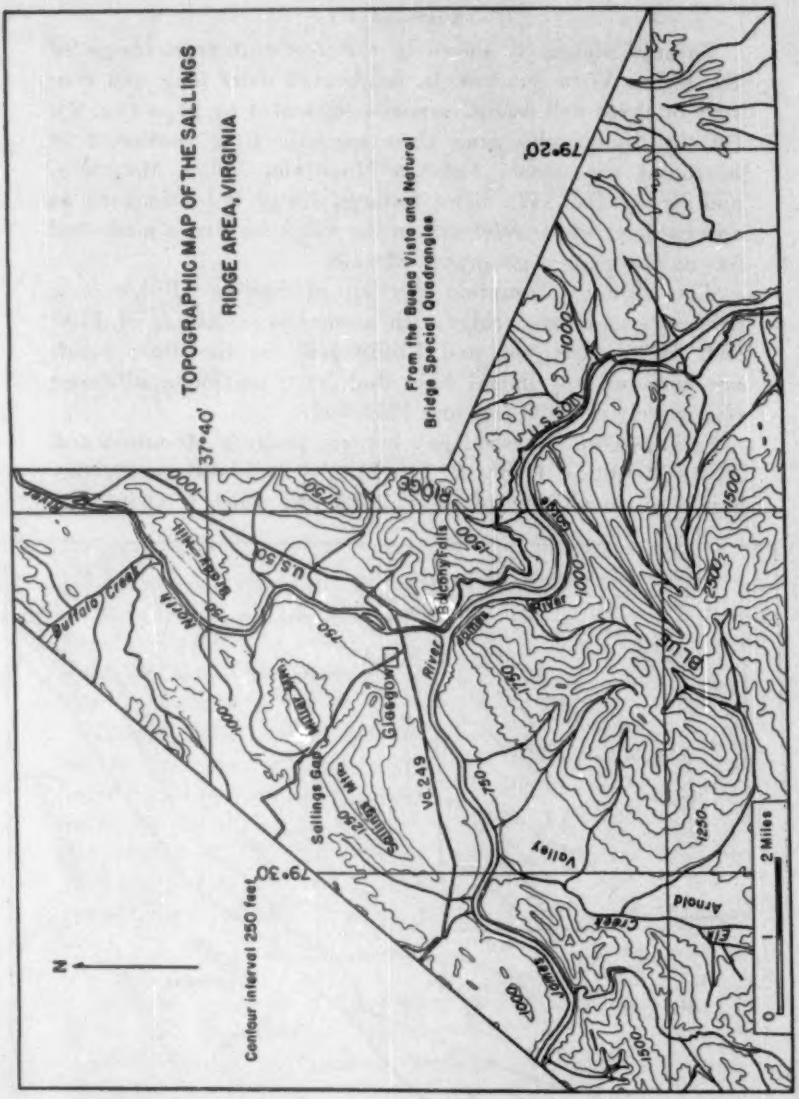

Fig. 2. Topographic map of the Sallings Ridge area (from the Buena Vista and Natural Bridge Special quadrangles).

feet lower than the average elevation of the Harrisburg erosion surface to the northwest. From Sallings Gap down to the flood-plain of James River, about 1½ miles to the southeast, there is a difference in relief of about 400 feet.

North River flows between Miller Mountain and Brady Hill. The gap occupied by the river is conspicuously asymmetrical. North River flows along the southwestern side of the gap at the base of a steep slope. The northeastern side of the gap is a comparatively gentle, terraced slope.

James River flows along the southeastern foot of Sallings Ridge to Glasgow, where it turns abruptly into a superb gorge through the Blue Ridge at Balcony Falls. North River, from the northeast, enters James River at the entrance to the gorge, 2 miles downstream from Sallings Ridge (fig. 2).

STRATIGRAPHY

TABLE 1

Sequence of Formations in The Sallings Ridge Area

Age	*Formation*	*Approximate Thickness Feet*
Upper Cambrian	Conococheague formation	
Middle Cambrian	Elbrook formation, thin-bedded (platy) to thick-bedded gray banded limestone and dolomite....	1700
Lower Cambrian	Rome formation, red and yellow shale and gray banded limestone and dolomite	1850
	Shady dolomite, basal dolomitic sandstone overlain by thick-bedded gray dolomite	1300
	Erwin quartzite, thick-bedded gray and white arenaceous quartzite	600
	Hampton formation, interbedded gray banded siltstone and gray and white arenaceous quartzite	1000
	Unicoi formation, basal graywacke conglomerate and volcanics overlain by gray arkosic siltstone and conglomeratic quartzite	450
Precambrian	Granitic Complex	

Sallings Ridge is capped by Erwin quartzite, which is conformably overlain by Shady dolomite at the southwestern end of the mountain (fig. 3). The Rome formation crops out

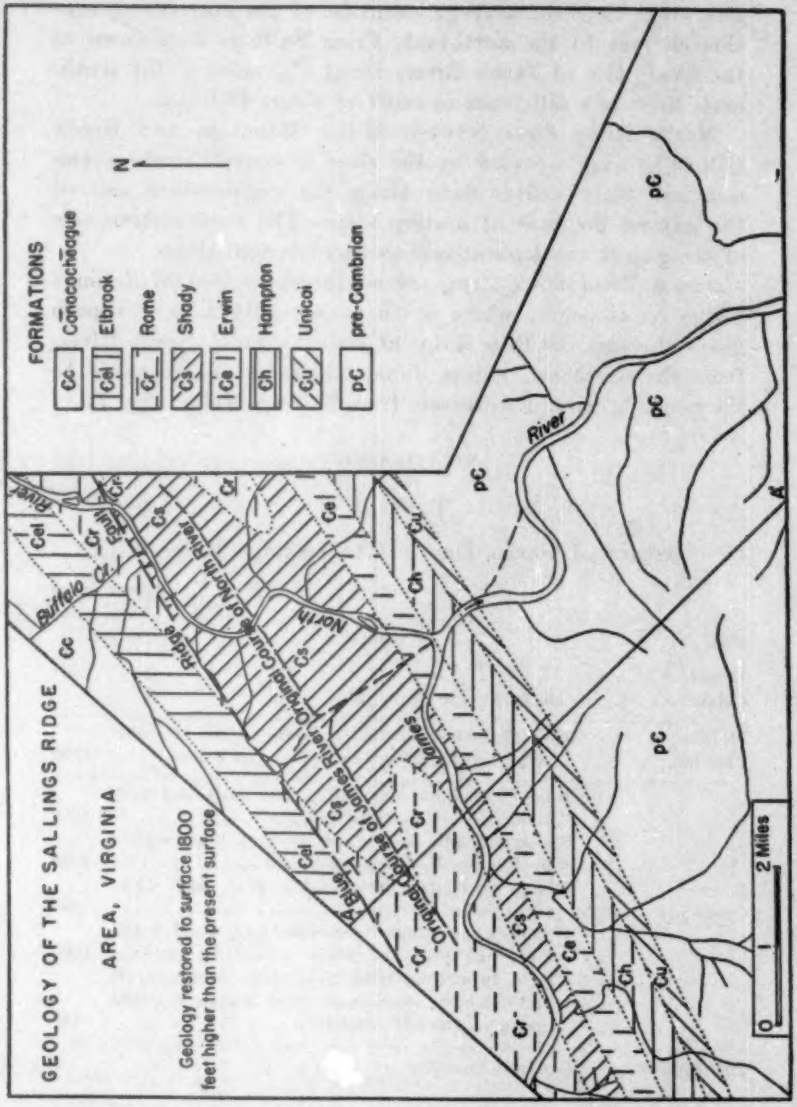

Fig. 3. Geologic map of the Sallings Ridge area.

along the lower slopes of the mountain and underlies the valleys of James and North Rivers. The Elbrook formation crops out near the northwestern foot of Sallings Ridge.

Southeast of Sallings Ridge, across the valley of James River, the Shady, Erwin, Hampton, and Unicoi formations and the Precambrian granitic complex form parallel outcrop belts in the Blue Ridge (fig. 3).

STRUCTURE

The geologic structure exposed in the Sallings Ridge area consists of an autochthonous complex and remnants of an allochthonous complex separated by a folded overthrust. The overthrust was folded after the associated strata were folded. This structural discordance has been revealed by the erosion of large re-entrants into the fault block (figs. 3, 4).

The fault in Sallings Ridge is named the Blue Ridge fault on the Geologic Map of Virginia (Virginia Geological Survey, 1928) and the Fries fault by Stose and Stose (1949, p. 305). Detailed studies in central Virginia have not substantiated the existence of a single great overthrust along much of the Blue Ridge such as the Blue Ridge or Fries Fault. There is a zone of overthrusts formed by a succession of laterally overlapping faults. These faults emerge from beneath an overthrust at one end of the trace and disappear in a crystalline complex at the other. It is, however, expedient to refer to the principal fault in the Sallings Ridge area as the Blue Ridge fault.

This fault, in the Sallings Mountain area, lies along the southeastern foot of the Blue Ridge northeast of James River gorge. Southwest of the gorge the trace crosses the Blue Ridge and encircles Sallings Ridge in the Valley and Ridge province (fig. 3). Southwest of Sallings Ridge the fault is exposed for many miles at the northwestern foot of the Blue Ridge in the valley of James River (plate 1, fig. 1).

Sallings Ridge is in a lobe in the forefront of the allochthonous block of the Blue Ridge fault and consequently closely resembles a klippe. The Sallings Ridge mass, however, has not been completely detached from the main mass of the thrust block. James River has eroded a valley through the edge of the thrust block parallel to the strike of the fault, except in

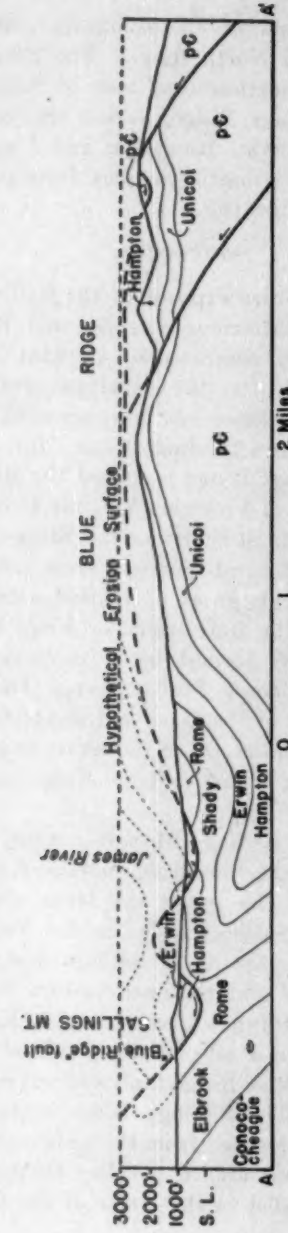

Fig.4. Structure section A-A'. (See figures 3 and 4).

a narrow "isthmus" between Sallings Ridge and the Blue Ridge (fig. 3).

Because of folding, the dip of the Blue Ridge fault in the Sallings Ridge area varies both in amount and direction (fig. 4). Prior to folding, the fault dipped gently southeast. Had there been initially a steep dip the folds would be inconspicuous and there would be no reversals in dip. Along the southeastern foot of the Blue Ridge the dip is about 22° SE. Northwestward the fault arches over the Blue Ridge in the form of a large anticline. The amplitude of this fold is greater than the local relief of the Blue Ridge. Other smaller folds are shown on the geologic map and cross section (figs. 3, 4).

The regional strike of the Blue Ridge fault is northeast. The westward strike, southwest of James River gorge, is due to the folding of the fault. The major anticline in the fault clearly plunges southwestward and the fault trace changes strike around the end of this fold.

A belt of mylonite, formed from Precambrian granitic rocks, occurs along the Blue Ridge fault at the southeastern foot of the Blue Ridge. This mylonite disappears where the strike of the fault changes at the end of the large anticline in the overthrust southwest of James River gorge (fig. 3). The localization of mylonite suggests that during a renewal of movement the fault was thrust against the southeastern limb of the fault-surface anticline and, in effect, was deflected upwards. Intense granulation and milling action produced mylonite along the zone of deflection.

As shown in the accompanying structure section (fig. 4), there is no conformity among the folds in the allochthonous block, fault surface, and autochthonous block. The folds in the allochthonous block were formed to the southeast and were thrust northwestward upon those in the autochthonous block. After faulting there was a second episode of folding which is clearly represented by the folds in the fault. Folds such as those in the fault hardly could have been formed by changes in dip as the fault developed because they are comparatively steep-limbed folds and one appears to be locally overturned (in Sallings Ridge).

The quartzite in Sallings Ridge is brecciated. This brecciation appears to have been caused by folding. The anticline

of quartzite in the ridge is contained in the younger syncline in the fault (fig. 4). The formation of this syncline must have imposed severe strain upon the anticlinal quartzite. Because the magnitude of readjustment is less in the trough of the younger syncline in the fault and greatest above the fault between the limbs of this syncline, there should be a corresponding variation in the degree of brecciation. Such an analysis is supported in Sallings Ridge where there is no brecciation at the ends of the fault-surface syncline and much brecciation within the fold (plate 1, fig. 2).

Campbell and others (1925, pp. 45, 82, 84, 91-93) recognized two distinct intervals of folding separated by an interval of overthrusting in the Valley and Ridge province south of the Sallings Ridge area. These writers state that "the Appalachian 'revolution' was of spasmodic character and . . . . some of the folds and faults are very much older than others of similar form and character." Fourmarier (1936, pp. 122-123) has shown that overthrusts in the Valley and Ridge province were formed after the rocks were first folded. He refers to folded faults and thus recognizes an interval of folding after the faults were formed. Cooper and Haff (1940, p. 948), on the other hand, state that the Pulaski and Max Meadows overthrusts in southwestern Virginia were formed prior to the folding of the associated strata, but after the folds northwest of the faults. The older folds to the northwest, Cooper suggests (1939, pp. 55, 64-66), acted as a buttress against which the overthrusts terminated.

The well exposed relations in the Sallings Ridge area seem to be clearly indicative of multiple deformation and structural discordance.

AGE OF DEFORMATION

All of the consolidated rocks in the Sallings Ridge area are Cambrian or older while the deformation is younger than Cambrian. There are, therefore, no stratigraphic units by which the ages of deformation can be determined. There were clearly three stages of deformation separated by intervals of unknown duration. These stages are evidenced by (1) the folding of the rocks in the allochthonous and autochthonous blocks, (2) the formation of the overthrust, and (3) the

Plate 1

Fig. 1. The Hampton formation thrust on Shady dolomite along the Blue Ridge fault near Buchanan, Virginia, southwest of the Sallings Ridge area.

Fig. 2. Brecciated Erwin quartzite in Lone Jack quarry in Sallings Ridge.

Plate 2

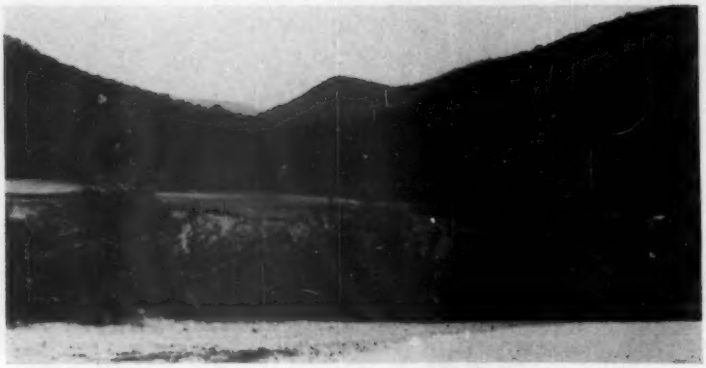

Fig. 1. Sallings Gap from the west.

Fig. 2. Boulder of Erwin quartzite in Sallings Gap.

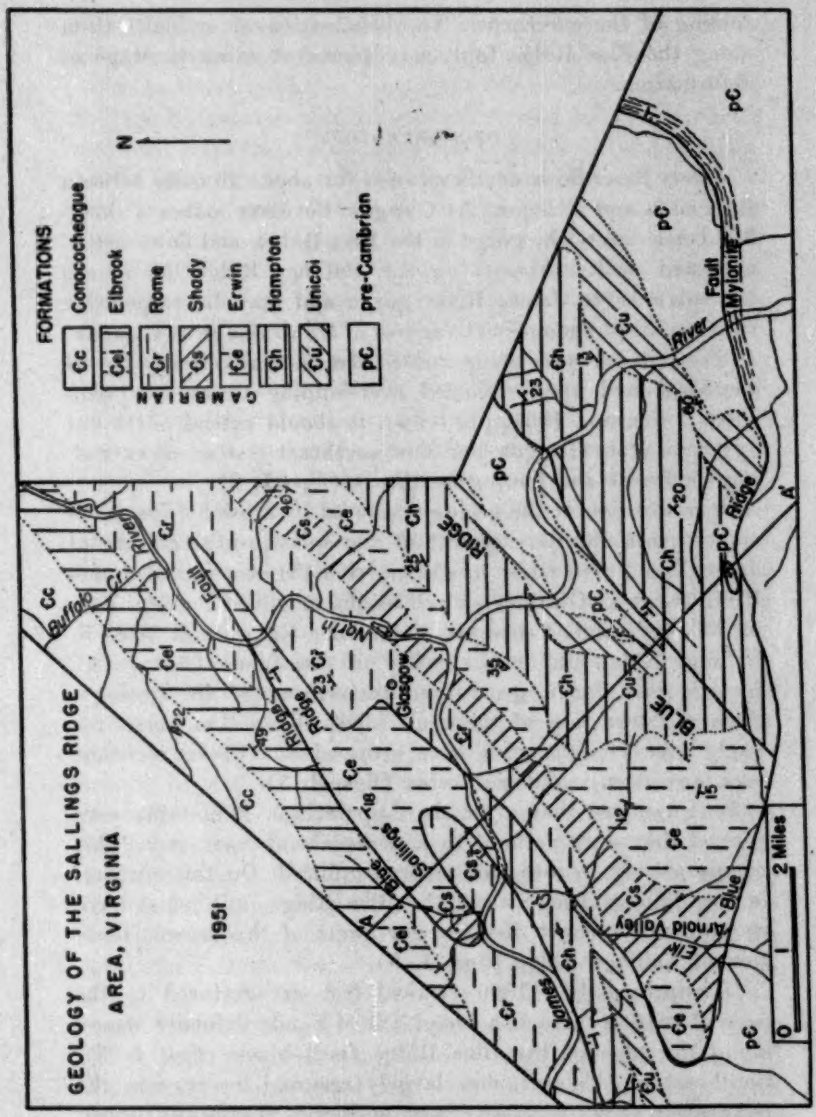

Fig. 5. Generalized restoration of the geology of the allochthonous block of the Blue Ridge fault in the Sallings Ridge area. This map also shows present and the postulated former courses of James and North rivers in the area.

folding of the overthrust. The localization of mylonitization along the Blue Ridge fault may represent a fourth stage of deformation.

GEOMORPHOLOGY

James River flows northeastward for about 20 miles between Buchanan and Glasgow. At Glasgow the river makes a sharp 90° bend, enters the gorge in the Blue Ridge, and flows southeastward to Lynchburg (fig. 1). Sallings Ridge lies across the entrance to James River gorge and may be responsible for the abrupt change in the course of the drainage at Glasgow. If James River were a superposed stream that initially flowed southeastward upon unfolded over-lapping Cretaceous sediments (Johnson, 1931, pp. 3-54), it should extend northwest upstream from Glasgow and flow southeast instead of extending southwest and flowing northeast (figs. 1, 2).

A restoration of the geology removed by erosion (figs. 4, 5) may explain the development of the subsequent segments of James and North rivers upstream from the west end of James River gorge at Glasgow as well as the origin of Sallings Gap in Sallings Ridge. Remnants of the Blue Ridge fault block in Sallings Ridge and in the valley of the James (figs. 3, 4) furnish data for a generalized restoration of the geology. Such a restoration of the fault block shows that comparatively non-resistant rock once cropped out where resistant rock now occurs and vice versa (figs. 3, 5).

It is assumed that after the Appalachian Mountains were formed they were reduced to a peneplain at least once. This comparatively smooth surface was uplifted. On this surface, in the Sallings Ridge area, the Blue Ridge fault must have cropped out a short distance northwest of the present location of Sallings Ridge (figs. 4, 5).

If approximately 1800 vertical feet are restored to the present erosion surface, a broad belt of Shady dolomite occurs along the edge of the Blue Ridge fault block (figs. 4, 5). Southeast of this belt, now largely removed by erosion, the restoration shows successive belts of Erwin, Hampton, Unicoi, and Precambrian rocks. The Blue Ridge, at this time, presumably did not form a distinct topographic unit with a valley along the northwestern foot. Sallings Ridge was not in evi-

dence. The surface probably was characterized by gently undulatory terrain gradually rising northwestward.

James River probably began its development east of the Sallings Ridge area as a consequent stream advancing northwestward from the sea up the slope of the uplifted peneplain. As the stream advanced headward across the metamorphic, granitic, and quartzitic rocks to the broad belt of Shady dolomite on the margin of the Blue Ridge fault block, there was little difference in resistance to the formation of its valley. Upon reaching the Shady outcrop belt, however, the headwaters found brecciated (pp. 647-648) Shady dolomite much less resistant to weathering and erosion than the rocks to the northwest. Branches extended southwestward and northeastward along the strike more rapidly than northwestward across more resistant rocks (fig. 5). Thus subsequent valleys were formed and the Blue Ridge began to emerge as a distinct unit. Eventually the Shady in the Sallings Ridge anticline was penetrated down to the Erwin quartzite. As the quartzite was excavated the subsequent tributaries migrated laterally down the limbs of the anticline toward less resistant rock. The "James River" branch moved laterally southeastward from the quartzite belt and the "North River" branch moved laterally northwestward so that one branch flowed on one side and one on the other side of the emerging quartzite ridge. The "North River" branch was separated from the "James River" branch by a short segment which flowed across the resistant quartzite. This segment across the resistant quartzite belt formed Sallings Gap and delayed the development of North River with respect to James River which consequently became the master. Eventually North River abandoned Sallings Gap for the present gap because the younger gap was lower and the quartzite belt there was narrower (figs. 2, 3). The diversion (capture) was effected by a branch of the James a short distance downstream from the larger branches near Sallings Gap. After they were well established in their courses, James and North rivers penetrated the rocks in the Blue Ridge fault block and were thus "superposed" upon the rocks upon which they now flow.

Wright (1925, p. 53; 1936, pp. 61, 73-76) believes that Sallings Gap, which he states is one of the finest examples of

a wind gap in the Appalachians (plate 2, fig. 1), was formed by Cedar Creek (fig. 1). This creek rises in Short Hills and flows southeastward into the James about 5 miles southwest of Sallings Gap. In Sallings Gap, there are numerous waterworn boulders and cobbles of red Silurian sandstone and white Cambrian quartzite (plate 2, fig. 2). The nearest Silurian sandstone to Sallings Gap is in Short Hills about 7 miles to the northwest (fig. 1). There are no outcrops of Cambrian quartzite northwest of Sallings Ridge. It thus seems unlikely that Cedar Creek could have flowed through Sallings Gap bearing the assortment of boulders and cobbles found there. Although the Cambrian quartzite might have come from the core of Sallings Ridge, the narrowness of the quartzite belt, distribution of the debris, and waterworn character of the boulders and cobbles seem to indicate derivation from another belt. If the Cambrian quartzite debris were transported into the gap, the combination of cobbles and boulders from Cambrian and Silurian rocks could have been transported only by a stream that received sediment from the southeast (Blue Ridge) and the northwest (Valley and Ridge province). The only streams that adequately fulfill this requirement are James and North rivers. The James, southwest of Sallings Ridge, receives sediment from the Lower Cambrian in the Blue Ridge, but this sediment is derived from the Hampton and Unicoi formations of banded rocks and conglomerates not represented among the boulders and cobbles in the gap. North River, on the other hand, receives an abundance of sediment from the Lower Cambrian Erwin quartzite in the Blue Ridge between Buena Vista and the gap. Sediments from Silurian formations are transported by Buffalo Creek to North River about 3 miles upstream from the gap (fig. 1).

Another feature that favors North River as the former occupant of Sallings Gap is a valley that extends from the gap to North River along the northwest foot of Sallings Ridge (fig. 2). This valley now contains two small possibly misfit streams. North River may have occupied this valley until captured and diverted through the present gap between Miller Mountain and Brady Hill.

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THE PRESENT-DAY SNOWFALL OF LABRADOR-UNGAVA

F. KENNETH HARE

ABSTRACT. It is possible for the first time to draw approximate distribution maps of snowfall in Labrador-Ungava, where the Wisconsin Laurentide ice-sheet is believed to have originated. The observed distributions are tentatively explained in the light of (a) the present-day path of moisture-bearing cyclones, and (b) the presence of unfrozen seas and lakes. Inferences are made that such open water areas may have influenced the accumulation of ice at the beginning of Wisconsin time. The view of Antevs and Enquist that northeasterly airstreams bring snow in large quantities is discounted.

INTRODUCTION

MUCH has been written about the plateau of Labrador-Ungava as the presumed place of origin of one of the major dispersal centres of the Wisconsin ice. In recent years controversy has centred upon the conflicting views of Antevs and Flint as to the origin and character of this ice. Flint maintained that a single ice-sheet—the Laurentide—produced the drift formerly assumed to be the deposits of separate centres in Keewatin and Labrador (1943, pp. 332-3). He further argues that the Laurentide sheet was first formed in the high eastern rim of the Labrador-Ungava plateau, and in the even higher ranges of eastern Baffin Land, subsequently spreading westwards to engulf the modern site of Hudson Bay, and ultimately extending to a contact with the Cordilleran Sheet (1943, p. 356). Antevs (1945), on the other hand, holds that the Keewatin centre originated as an eastward extension of the Cordilleran sheet. The Labrador ice remained distinct.

Many of the differences between the two viewpoints arise from different pictures of the climate that led to the accumulation of snowfall in the area of origin. Enquist (1916) and later Antevs (1945) maintained that the snow fell mainly from northeasterly airstreams from the Atlantic, whose frequency was increased by the prior development of ice-sheets over Greenland and Scandinavia. Flint (1943, p. 348), however, supports the widely held opinion that the moisture required was advected from the southwest, being precipitated along the fronts of cyclones crossing the Labrador plateau or the flanks of the ice-sheet.

Both of Flint's more recent papers have been characterised

by a very detailed examination of the meteorology of Wisconsin times. In 1945 he combined with Dorsey (1945) to deduce the weather typical of the glaciation by applying the principle of the so-called circulation index. These writers concluded that the snow which fed the nascent glaciers fell from southwesterly airstreams along the fronts of "Alberta" cyclones, which travel across central and southern Labrador-Ungava at times of high index.

In recent years a number of climatological stations have been established inland in Labrador-Ungava, from which there had hitherto been little or no information. By adding these to the pre-existing records of coastal stations, it has been possible to draw rudimentary maps of snowfall across the peninsula. These maps are presented and discussed in this paper in the hope that they may throw some light on the controversies surrounding the origin of the Wisconsin ice.

THE EXISTING DISTRIBUTIONS

Figure 1 shows the network of climatological stations from which observations were obtained. A detailed specification of these stations was given by the present writer in the appendix to a recent article (1950). Most of them are (or were) stations of the Canadian Meteorological Service or the U. S. Air Weather Service, but a few were maintained by the Moravian Brethren on behalf of the Deutsche Seewarte. In all cases, snowfall at these stations is measured by the ordinary fixed ground-stick method. The difficulties of observing snow in the windy Eastern Arctic are formidable; furthermore, some of the stations were formerly staffed by inexpert personnel, and it is very likely that some of the observations are unrepresentative. The drawing of all the maps presented below is distinctly subjective, the author having drawn heavily upon his own knowledge of the relief of the region in completing the isopleths.

The mean annual snowfall over the eastern Canadian Arctic and sub-Arctic is shown in figure 2. The salient features are worth itemizing:

(1) Over northern Keewatin and most of the Arctic Archipelago snowfalls of less than 50 inches are widespread. Falls of less than 75 inches are general in Manitoba, and southern Keewatin.

(2) A broad area of heavy snowfall extends across the southern half of the Labrador-Ungava plateau from the Upper Ottawa and St. Maurice valleys to the Atlantic coast, including Newfoundland. Falls are heaviest (a) along the Laurentide scarp (here about 3,000 ft. high) north of the North Shore of the Gulf of St. Lawrence, and (b) in south-easternmost Labrador, where Harrington Harbour and Cartwright both report over 200 inches.

(3) Much lower falls occur in the James Bay basin, round Ungava Bay, and in the Lake St. John basin. Some doubt exists as to the snowfall on the east coast of Labrador. The records of the old Moravian mission at Ramah, at the foot

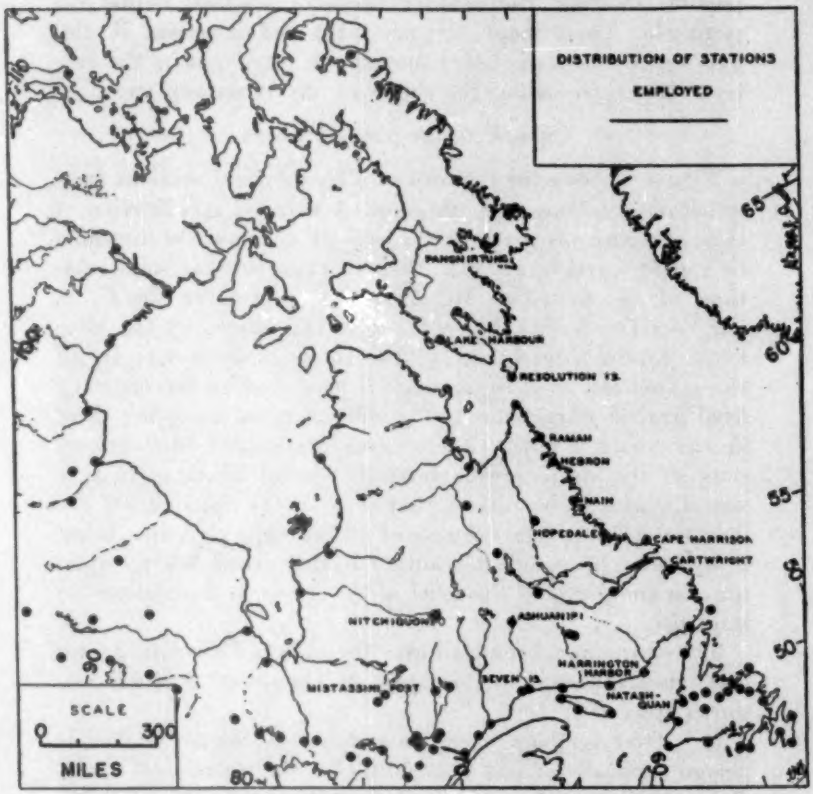

Fig. 1. Climatological stations in eastern Arctic and sub-Arctic Canada. Place names are shown for stations mentioned in text.

of the Torngats, indicated a fairly abundant winter snowfall, whereas much lighter falls were typical at the nearby Hebron mission. Recent records at Nain and Cape Harrison also show a snowfall comparable with that in the interior. On the other hand the Marconi radio station at Hopedale indicates very light falls. The exceptionally windy, rugged and barren nature of this coast makes the observation of fresh snow very difficult, if not in some spots impossible. The Moravian missionaries reporting to the Deutsche Seewarte never attempted the measurement of snowfall at some of their stations, and abandoned it after a few years at others.

(4) A small area of significantly greater snowfall lies

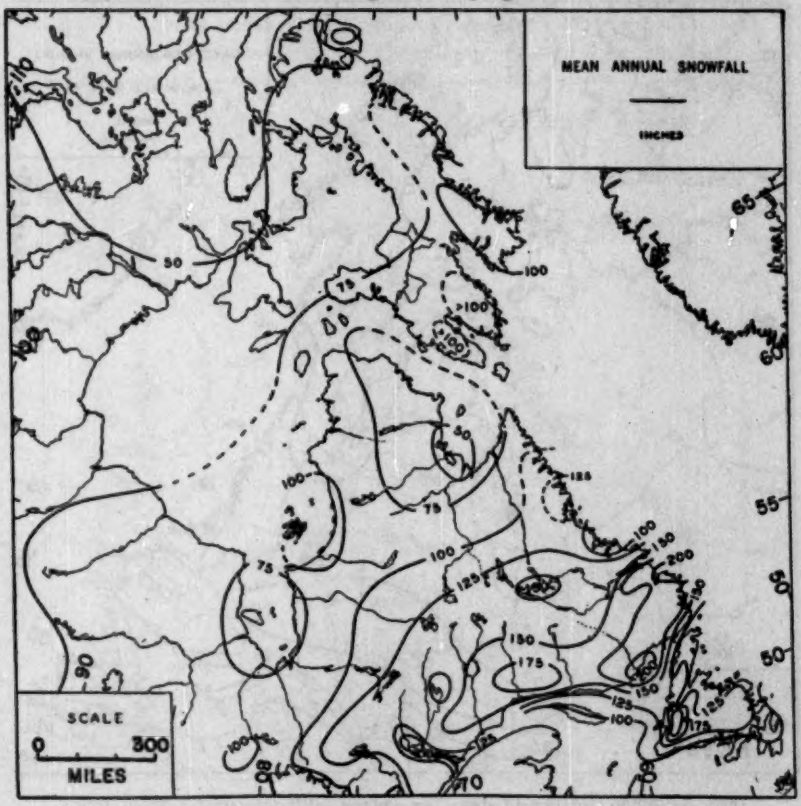

Fig. 2. Mean annual snowfall (in inches). Isopleths are dashed where their position is more than usually doubtful.

along the east coast of Hudson Bay (over 100 inches east of the Belcher Islands).

(5) Snowfalls of about 100 inches occur in places in southern Baffin Land, *e.g.*, Pangnirtung and Lake Harbour. Since these stations are in protected sites close to sea-level, it is certain that heavier falls must occur on the nearby mountains, on which numbers of small ice-caps are developed. It is impossible to guess how much greater these falls are than those at sea-level.

The most significant of these features is the heaviness of the snowfall all across the central and southern districts of the

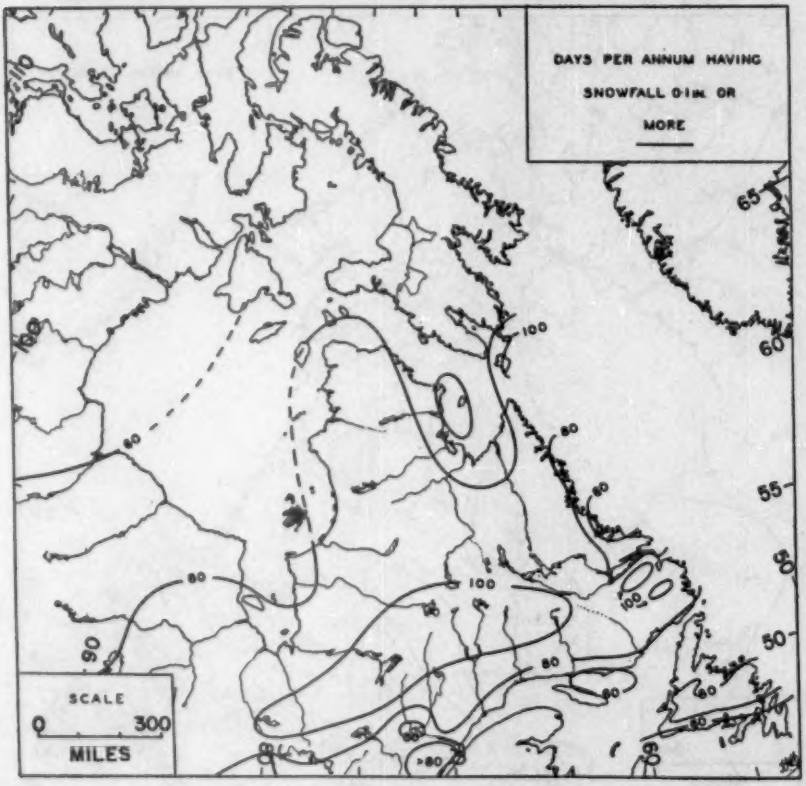

Fig. 3. Mean number of days per annum with measurable snow (over 0.1 in.). This map has not been taken north of Southampton Island because of the sparsity of data.

plateau of Labrador-Ungava. More than half the entire peninsula has falls of over 100 inches. This, moreover, is the belt of most frequent snowfall, the axis of highest frequency (over 100 days with 0.1 in. snow per annum) running from Lake Abitibi to the Mealy Mountains via Lakes Mistassini, Nitchequon and Ashuanipi (fig. 3).

An attempt is made in figures 4 and 5 to show how the distribution of mean snowfall over Labrador-Ungava changes during the winter. November (fig. 4) shows the pattern typical of the early winter. At this season much of the precipitation falls as rain along the southern margins of the region, and the main snowy belt noted on the annual map (fig. 2) across south-central districts is not yet conspicuous. Very noticeable, however, is the heavy snowfall on the east

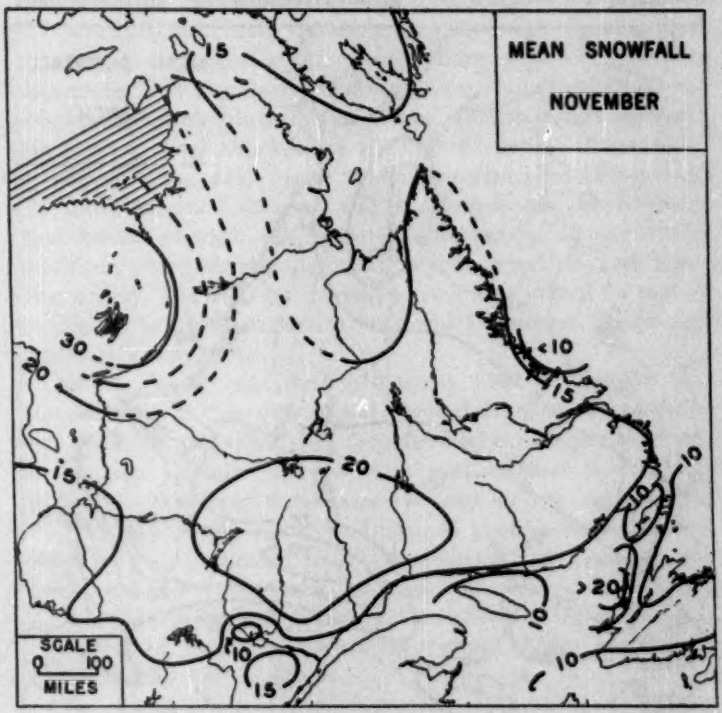

Fig. 4. Mean snowfall for November (inches). Note the heavy fall along the Hudson Bay shore south of the area believed to be frozen at this time (frozen area shaded obliquely).

coast of Hudson Bay south of Portland Promontory. This last area is discussed later. There is also a patch of heavier snowfall on the west coast of Newfoundland.

Figure 5 shows the distribution in March, a month typical of late winter. The Hudson Bay coastal belt so conspicuous in November has now entirely vanished. The south and central regions have everywhere over 15 inches, falls being heaviest along the North Shore of the Gulf of St. Lawrence, and on the Labrador south of Hamilton Inlet. In some parts of this last area, falls exceed 40 inches for the month.

ORIGIN OF THE SNOWFALL

There can be little doubt that the greater part of the snow comes from the fronts of eastward or northeastward moving cyclones. In every month from December to April the belt

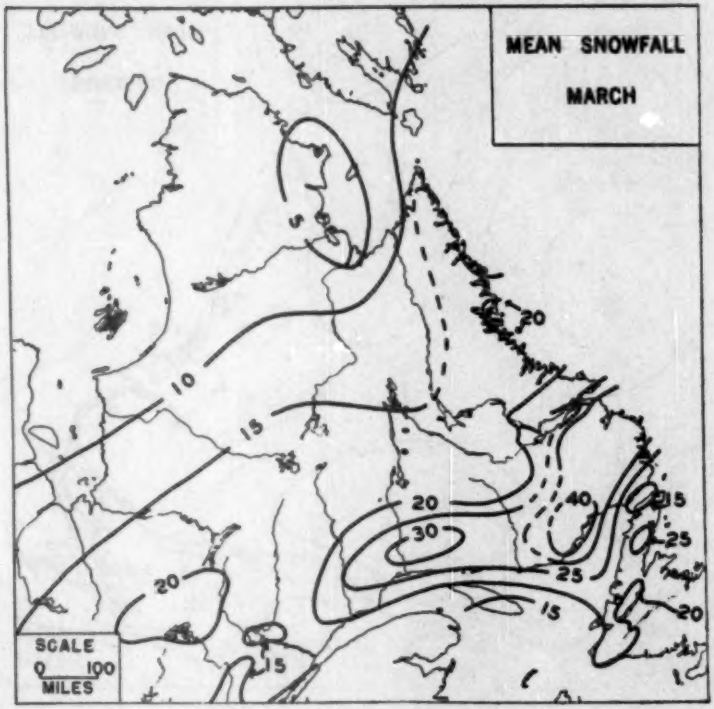

Fig. 5. Mean snowfall for March (inches). Note the absence of a snowbelt along the east shore of Hudson Bay.

of heaviest snow runs east-north-eastwards across the southern half of Labrador-Ungava, just north of the belt of maximum frequency of frontal activity. Flint and Dorsey (1945, p. 629) maintained that much of the snow falls from "Alberta" cyclones of the type that traverses eastern Canada from the west during periods of unusually strong westerlies in the middle and upper troposphere. They argue further that these upper westerlies increased in strength at the onset of the Wisconsin glaciation, and ascribe the origin of the Laurentide ice-sheet to an increased snowfall from Alberta cyclones on the higher parts of Baffin Land and Labrador-Ungava.

The observed distributions of snowfall are consistent with this argument. Leighly (1949, pp. 142-143), however, has pointed out that the southern part of Labrador-Ungava stands at the cross-roads of the continental cyclone paths. He confirms Flint and Dorsey's hypothesis by showing that months whose snowfall on the North Shore of the St. Lawrence was more than double the average were characterised by an average zonal circulation index about 1.0 mb. above normal.[1] He argues, nevertheless, that the cyclone paths of low index conditions (*viz.*, weak upper westerlies) also tend to converge on southeastern Labrador and Newfoundland; he contends that heavy snowfall will occur in these areas in any winter month in which there is abundant cyclonic activity, of whatever origin. The distribution maps given here afford no certain verdict on Leighly's argument, with which, however, the present writer is in agreement.

Antevs (1945) and earlier Enquist (1916) thought that the snowfall of this region was derived from maritime polar air from the Atlantic, *i.e*, from easterly circulation. Since such winds are now infrequent in winter, these writers had to assume that they were more frequent at the beginning of the Wisconsin age. Antevs maintained that such an increase could only be obtained if the semi-permanent Icelandic low were displaced southward. This might be achieved, he thought, if the Greenland and European ice-sheets were already in existence, as the high pressure they would induce would drive the Icelandic low south.

[1] The "zonal circulation index" is the difference of mean pressure between latitudes 35° and 55° N. It is a good measure of the strength of the upper westerlies to which Flint and Dorsey refer.

Flint and Dorsey (1945, p. 634) dismissed this hypothesis, stating that "...the eastern slopes receive a relatively small amount of orographic snowfall from Polar-Atlantic air, but most of the snow falls on both eastern and western slopes from overrunning warm, moist air having southerly rather than easterly components aloft." They did not give any reasons for their opinion. Actually appreciable snowfall may develop in onshore airstreams. In the majority of instances this snow comes, as they said, from southerly airstreams aloft, merely falling to the surface through the easterlies. But the present author can recall several instances of heavy snow from onshore airstreams where frontal overrunning could not pos-

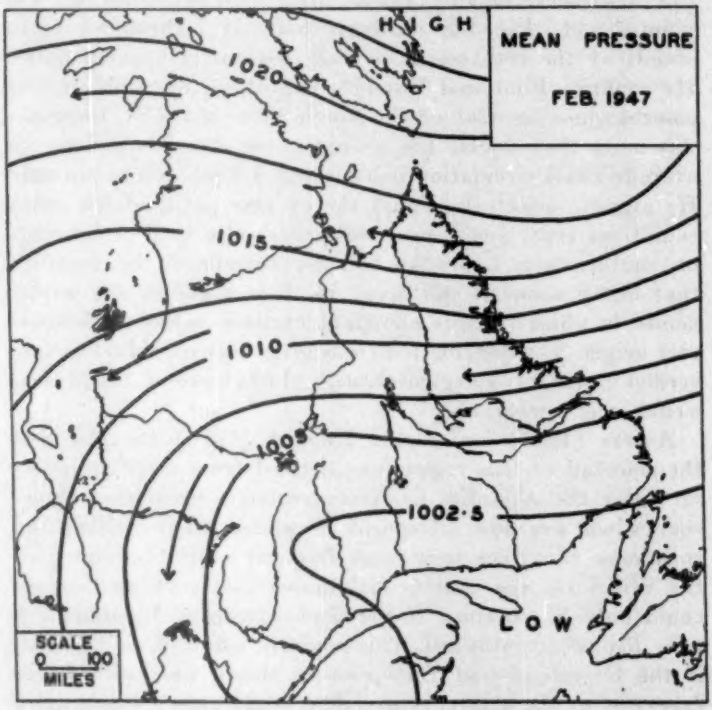

Fig. 6. Mean sea-level pressure, February, 1947. The mean flow of he air over the month as a whole was *parallel* to the isobars in the sense shown by the arrows. Northern and central Labrador-Ungava were thus covered by an easterly flow from the Atlantic, as specified for Wisconsin times by Enquist and Antevs. Pressure is in millibars.

sibly be invoked. Such snowfall rarely extends far inland, but is often observed at Goose Bay airport.

An excellent test of Antevs' hypothesis was afforded by the anomalous month of February, 1947. In that month persistent high pressure developed over Northern Europe and Greenland; the main centre of cyclonic activity was far to the south, lying across southernmost Labrador-Ungava, the Gulf of St. Lawrence and Newfoundland. Labrador-Ungava, Hudson Bay and the eastern Canadian Arctic generally were covered for most of the month by easterly airstreams from the Atlantic.

Figure 6 shows the mean pressure distribution over Labrador-Ungava for the month in question. Since the wind at low-levels flows parallel to the isobars, and anti-clockwise round low pressure centres, the whole northern and central part of the peninsula was plainly covered by easterly currents from the Atlantic as Antevs postulated. The low pressure area over Newfoundland and the Gulf of St. Lawrence, with the trough extending westwards, represented the path of numerous cyclones, most of which travelled eastwards from the Great Lakes region, or northwards from the Atlantic states.

At first sight the map of snowfall for the same month (fig. 7) appears to confirm Antevs. Heavy snow fell in eastern Labrador-Ungava, heaviest falls being on the coast near Cartwright (56 inches). The western half of the peninsula received much less. It is clear, however, that the heavy snow area lay immediately north of the low pressure trough. Farther north, the onshore winds brought progressively less snow; at Resolution Island, where the flow was very continuously from east or southeast, only 3 inches of snow fell. *In short, the very heavy snowfall occurred precisely where we should have predicted it would fall if it were largely derived from overrunning warm air of southerly origin (above the surface easterlies) in the cyclonic disturbances that passed through the Gulf of St. Lawrence.*

An inspection of the daily weather maps confirms this analysis. On several occasions, however, considerable snow fell at coastal points in Labrador from deep easterly currents with no overrunning. This occurred only where the flow was being controlled by nearby cyclonic centres of fully occluded type.

It seems that appreciable snow in onshore streams only occurs where there is surface convergence in progress, and the flow is cyclonically controlled.

A more serious objection to Antevs' hypothesis is that the frequent presence of maritime air from the Atlantic over eastern Canada would inevitably destroy the winter cold. Even if we assume that the Atlantic was several degrees colder at the onset of Wisconsin time than it is today, it cannot have had a surface temperature below about 35° F. (+ 2° C) unless it had a consolidated pack-ice cover. It is improbable in actual fact that the pack-ice in the Labrador Sea and in the adjacent parts of the Atlantic was ever strikingly greater than it is in bad years today. Hence onshore winds must always have recently passed over a surface above the

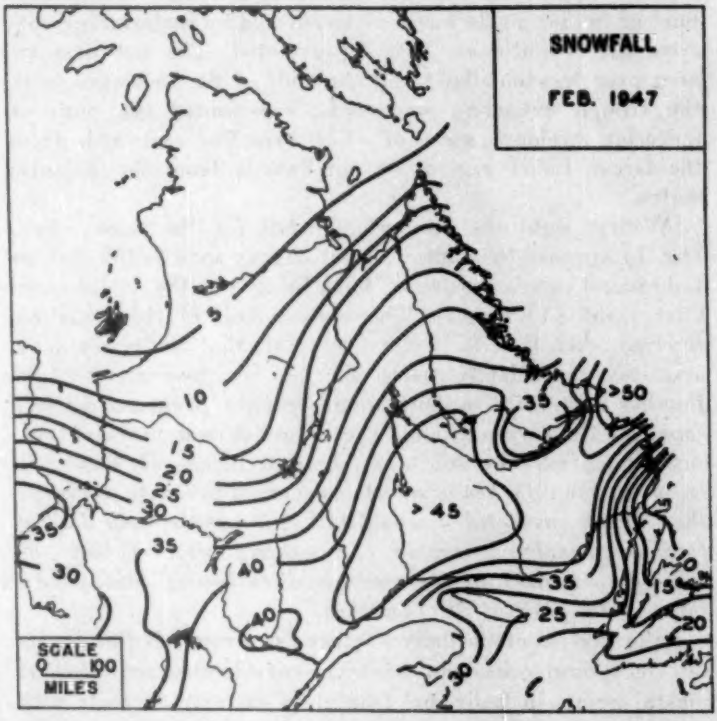

Fig. 7. Snowfall in February, 1947 (inches), a month of easterly winds (see figure 6).

freezing point; today they enter Labrador even in mid-winter with temperatures between +25° F. and +30° F., having been chilled very little by their passage over possibly 150 miles of pack-ice in the Labrador current.

Persistent east and northeast winds, moreover, tend to prevent the southward drift of Labrador pack, and to disperse such pack if they become established in mid-winter.[2] Soule and Challender (1949, pp. 59-61) reported that the onshore winds of February, 1947 dispersed the Labrador

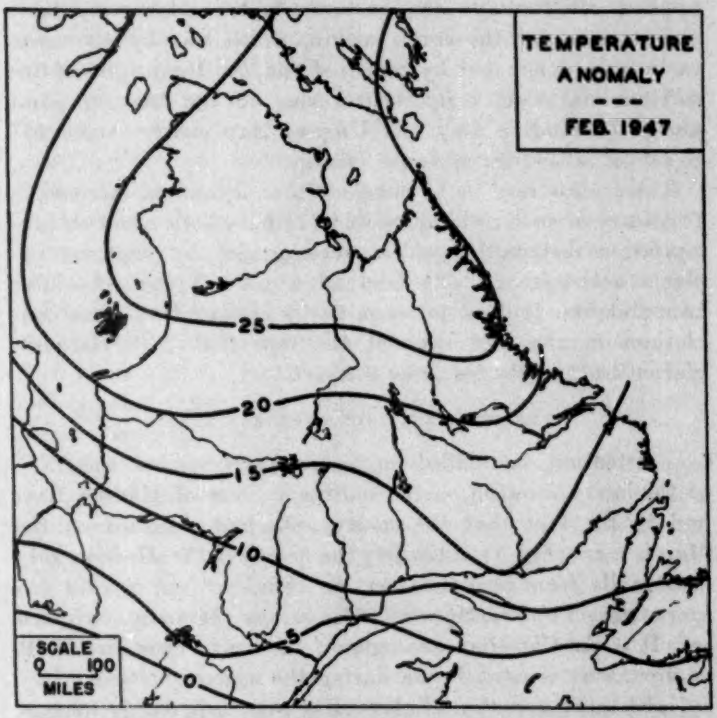

Fig. 8. Temperature anomaly in February, 1947. The isopleths show the number of degrees Fahrenheit by which actual temperatures *exceeded* long term normal values. The map shows very clearly the anomalous warmth introduced by the onshore flow described in figure 6.

[2] Wind-drift in pack-ice is directed somewhat to the *right* of the wind. Hence east winds off the Labrador tend to drift the ice with a component *northwards* along the coast. The southward drift of Labrador pack into Newfoundland waters proceeds only if westerly or northwesterly winds prevail off the Labrador. See Soule and Challender (1949).

pack along the entire coast, thus adding still more to the warm influence of the sea. If we suppose with Antevs that northeasterly winds were general at the beginning of the Wisconsin age, the sea off Labrador must have been to a large extent protected from pack-ice drift from the north.

Figure 8 emphasises these facts. It shows the deviation of air temperature from the long period mean in February, 1947. Over northern Labrador-Ungava temperatures were no less than 25° F. or more above average; similar figures applied all through the eastern Arctic. Moreover, these figures were for the entire month, which was by no means exclusively dominated by maritime air. At the height of the maritime invasion, temperatures rose to the freezing point along the Hudson Bay and Ungava Bay coasts—some 45° to 50° F. above the seasonal average.

These ideas lead us to conclude that a marked increase in frequency of easterly winds would (1) have little effect on precipitation distribution unless accompanied by vigorous cyclonic activity, and (2) lead to a marked rise of winter temperatures. It does not seem to the author that these conclusions in any way support the view that the Wisconsin glacier was largely fed from the east.

THE INFLUENCE OF UNFROZEN SEAS

Attention was called on figure 4 (November snowfall) to the heavy snowfall on the southeast coast of Hudson Bay, and to the fact that the snowy area had vanished on the March map (fig. 5). In brief, the snow on the Hudson Bay coast falls from heavy convection cloud set up in cold onshore currents of continental polar air by the warm, unfrozen sea. It is the Canadian analogue of the heavy snow that falls on northwest coastal Japan during the winter monsoon.

Until quite recently Hudson Bay was believed to remain unfrozen throughout the winter, in spite of the bitter cold of the prevailing northwest winds that cross it. It struck the present writer and his associates that such a situation should lead to very heavy snow along the east coast, probably in amounts similar to those experienced along the west coast of Honshu and Hokkaido, after the winter monsoon has crossed the unfrozen Japan Sea. Falls of as much as 200

inches in a single month have sometimes been recorded in the hills along this coast (London, Meteorological Office, 1945), and 50 inches a month is a commonplace in mid-winter in the north. During one snowy December (1927) at the little town of Takata, for example, 242 inches of snow fell, no less than 100 inches of which came during the last three days. Nearly all this avalanche of snow fell from simple convection showers set up in the cold monsoon as it approached the coast across the warm sea. Similar snowfall often develops along the southeast coast of Lake Erie, great inconvenience being experienced in Buffalo and Erie, Pa. from these heavy (and sometimes unpredicted) falls.

More recently it has been established that Hudson Bay freezes over completely by the New Year (Hare and Montgomery, 1949, pp. 88-89, 155-164). Apparently the freeze-up begins during November, final consolidation taking place late in December. Recent observations in late November (1949) showed that the eastern Bay was largely unfrozen south of latitude 60°, but was completely covered by thin, rafted pack north of that parallel (Montgomery, 1950, p. 42). In December the freeze-up continues apace, open water being confined by mid-month to the sheltered seas east of the Belchers and in James Bay. By early January the ice-cover is virtually complete.

The snowfall along the east coast behaves very much as this schedule would suggest. In November, the prevailing northwesterlies emerge from Keewatin with surface temperatures close to 0° F. In crossing the partly open Bay they are heated up some 20°-25° F., and are rendered thermodynamically unstable up to 7,000 to 10,000 feet (Burbidge, 1949). Heavy cumulus forms in the unstable lower layers, and snow-flurries are frequent. Over 30 inches of snow falls along the Ungava coast (fig. 4) of which some 15-25 inches can certainly be traced to the process just described, the rest being normal cyclonic snowfall. In December the snowfall continues, though reduced in scale by the progressive freeze-up.From mid-January onwards, there is no trace of convective snowfall, the few leads in the Hudson Bay pack being too small to bring about appreciable heating of the air above.

Similar open water snowbelts are visible elsewhere in eastern

Canada. Heavy November snowfall occurs on the west coast of Newfoundland, for example, when west winds approach across the unfrozen Gulf of St. Lawrence. Later in the winter a similar belt develops on the south Labrador coast around Harrington Harbour. Though the Gulf freezes over fairly compactly by January, there are usually patches of well-broken ice throughout winter west of Newfoundland in the saline and relatively warm Labrador current water that enters the Gulf round Capes Ray and Anguille. Southerly currents of returning continental polar air (such as always precede frontal systems approaching from the west) therefore reach the Labrador coast after travelling over a surface containing appreciable open water. The effect is greatly to intensify the frontal snowfall, turbulent convection cloud *below* the frontal mass adding considerable amounts of snow. Further west on the North Shore (*e.g.*, at Natashquan, Seven Islands), these cyclonically controlled southerlies approach across far more massive and consolidated pack, and snowfall is lighter. These facts show up well on the March map (fig. 5).

It is interesting to speculate on the influence that such unfrozen seas may have had on the origin of the Wisconsin ice. Even today, many small snow patches survive the summer on the east coast of Hudson Bay, which is rugged and upstanding. A small increase in winter snowfall might well produce large permanent snowfields on these uplands. It is by no means clear whether Hudson Bay existed during the pre-Wisconsin interglacial period. If it did, it might well have contributed heavily to the accumulating Wisconsin glacier over Labrador. If mean winter temperatures at the onset of glaciation were somewhat higher than they are today, the Bay would have remained unfrozen through the greater part of the winter. In such a case a winter snowfall of over 200 inches might have been expected along the east coast, an amount comparable with those experienced today in the snowiest part of the main cyclonic belt. Even if the Bay were frozen as early as at present, a higher frequency of cold westerly winds in the autumn months (as postulated by Flint and Dorsey) would give a heavier fall than is experienced in these regions today.

It seems quite possible that such snowfall may have ac-

celerated the westward spread of ice from its place of origin in the eastern part of the plateau of Labrador-Ungava. Obviously such a mechanism could only work if Hudson Bay were a large sea-area at the onset of glaciation. Until we know more of the pre-Wisconsin history of Hudson Bay, no final answer can be given on this tentative theory.

CONCLUSIONS

(1) Total annual snowfall is heavy today across central and southern Labrador-Ungava, and is low in the extreme north. The belt of heaviest and most frequent snowfall lies just north of the axis of maximum cyclonic activity.

(2) This distribution holds good throughout the winter months. In early winter, however, there is heavy snow on the east coast of Hudson Bay from showers in cold northwesterly currents, due to convection set up over warm open water. As the Bay freezes, this snowbelt disappears. If Hudson Bay existed before Wisconsin times, such snow may have assisted in the westward spread of the Laurentide ice-sheet. Similar open water influences are seen today around certain parts of the Gulf of St. Lawrence.

(3) The opinion of Enquist and Antevs that the Laurentide ice was fed by northeasterlies from the Atlantic is scarcely borne out by the evidence. The month of February, 1947, reproduced in a vigorous form the circulation visualized by Antevs. Heavy snow fell in southern Labrador-Ungava, but only near the trough-line of maximum cyclonic frequency; nearly all the snow fell from southerly airmasses overrunning the surface easterlies. In northern Labrador-Ungava falls were small, being less than 5 inches over the Ungava peninsula and southernmost Baffin. Moreover the prolonged easterly flow produced remarkably high temperatures. Great cold could not exist in Labrador-Ungava under such conditions.

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SOME TRIASSIC FRESH-WATER GASTROPODS FROM NORTHERN ARIZONA*

TENG-CHIEN YEN

ABSTRACT. Five species of Triassic freshwater gastropods are described, two of them new. These gastropods indicate that the enclosing deposit represents bottom sedimentation of a deeper water facies, and provide an authentic record to rectify both systematic and stratigraphic positions of two Triassic species of gastropods which were incorrectly determined as of Jurassic age.

THROUGH the kindness of Dr. James Steele Williams of the U. S. Geological Survey and Professor Edwin D. McKee at the University of Arizona, a small collection of gastropods was submitted to me for identification. The specimens were collected from the Echo Cliffs area north of Tuba City, Arizona, chiefly by Mr. Carl Klaenhammer but with two lots from an earlier collection of the Museum of Northern Arizona from the same general area. A preliminary examination of the specimens reveals that they are of fresh-water origin and comparable with some of the Chinle species of Upper Triassic age.

The new findings of more Triassic fresh-water gastropods in North America prove to be highly interesting because of the rarity of known records throughout the world. Any further discovery of similar kind will indeed enrich our knowledge in the gastropod fauna of Triassic time. The present collection contains the following species of gastropods:

"Valvata" gregorii Robinson
Triasamnicola cf. *T. pilsbryi* Yen and Reeside
Triasamnicola assiminoides, n. sp.
Triasamnicola sp. undet.
Lioplacodes canaliculatus, n. sp.

The assemblage of four of the above listed species, which were obtained by Mr. Klaenhammer from the same bed, apparently indicates that the enclosing deposit represents bot-

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tom sedimentation of a deeper water facies usually referred to as a littoral zone, where these prosobranchian species once existed and were buried with fragments of plants. The gastropods are in poor state of preservation, but they are not uncommon. The difference in size of the specimens representing the same species in the collection seems to imply the presence of younger stages of the species, which in turn may indicate that the enclosing deposit represents the original habitat area of these snails.

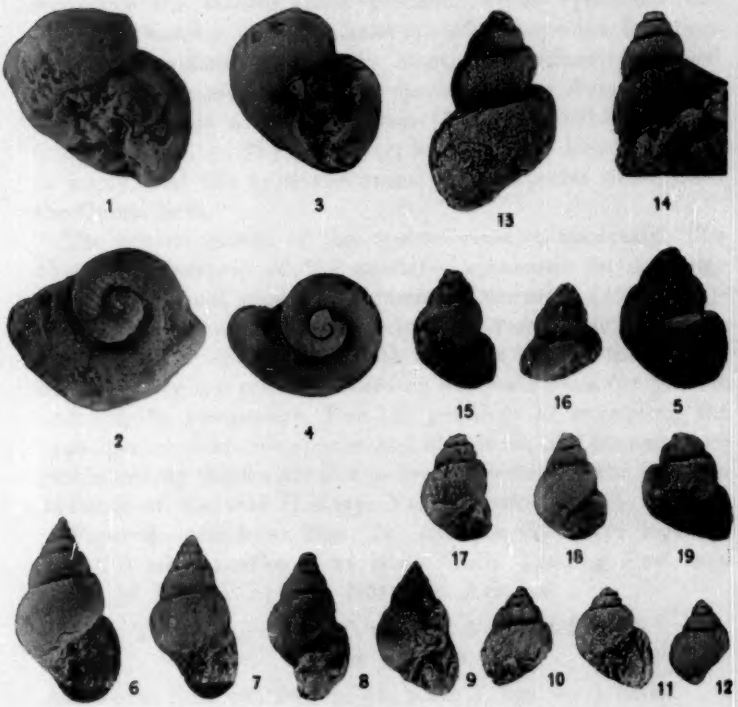
The collection provides an authentic record to confirm both systematic and stratigraphic positions of *Valvata gregorii* and *Limnaea hopii*, which Robinson (1915) described from northwestern Arizona and considered to be "closely allied" to forms of the Morrison formation. Furthermore, the present collection provides a record of the Triassic fresh-water gastropods in North America in addition to the first one, which was based on fossils collected in southern Utah by A. A. Baker (1946), of the U. S. Geological Survey, and described by Yen and Reeside (1946).

These gastropods, according to McKee (in correspondence) were collected from one of the thin but persistent cherty limestones of a marl series which occupies a position equivalent to "Division B" of the Chinle formation as defined by Gregory (1917). Gregory's Division B occurs at about the middle of the formation, which has been assigned a total thickness of 1,128 feet in the Navajo area. Moreover, some of these gastropods show specific identity and close relationship with those found by Baker in southern Utah. Baker's specimens were collected from a shale bed about 214 feet from top of the Chinle formation where it aggregates to a total thickness of 455 feet. The close resemblance in morphology of the fossils from northern Arizona and south Utah seems to indicate that the enclosing deposits are close in age. This interpretation may imply further that the two fossil-bearing beds are close in stratigraphic position although they may not be exactly equivalent.

"Valvata" gregorii Robinson
Plate 1, figs. 1-4.

Am. Jour. Sci., 4th ser., vol. 40, p. 649, fig. d, e, 1915.

Two internal molds in the collection, replaced by chert,



Figs. 1-4. *"Valvata" gregorii* Robinson x 2.
Fig. 5. *Triasamnicola* cf. *T. pilsbryi* Yen and Reeside x 2.
Figs. 6-10. *Triasamnicola assiminoides* Yen x 2.
Figs. 11-12. *Triasamnicola* sp. undet. x 2.
Figs. 13-19. *Lioplacodes canaliculatus* Yen x 2.

agree well with this species, described from the "Painted Desert beds" of northwestern Arizona, without exact data regarding the stratigraphic position. These specimens are somewhat smaller than the holotype of the species, but they may be considered specifically identical. Robinson assigned the time of deposition of this species to the Jurassic, and probably middle or late Jurassic (Robinson 1915, p. 651; Gregory 1917, p. 68). However, such specific identity seems to imply that the type specimens of the species came from the Chinle beds.

The generic status of this species remains uncertain. The observable features of the available specimens do not support the original generic assignment. Cossmann (1917) suggested that the species might belong to *Ampullaria*? (= *Pila* Roeding). The specimens in both the type lot and the present collection are too poor to afford an adequate basis for generic and specific assignment. For the privilege of examining the type specimens of this species and also those of *Limnaea hopii* Robinson, my thanks are due to the authorities of the Peabody Museum of Natural History, Yale University.

Figured specimens: Mus. N. Arizona G2-4257; locality: about 6 miles northeast of Black Falls Trading Post, and north of Badger Spring, Northern Arizona.

Triasamnicola cf. T. pilsbryi Yen and Reeside
Plate 1, fig. 5.

Am. Jour. Sci., vol. 244, p. 50, plate 1, figs. 9a-d, 1946.

A single specimen resembles closely *T. pilsbryi*, which was originally described from the Chinle formation of southern Utah. It differs by its much stouter outline of shell and broader body whorl.

Figured specimen: Mus. N. Arizona G2-4056; locality: "3 miles south of the Gap Trading Post," Arizona.

Triasamnicola assiminoides Yen, n. sp.
Plate 1, figs. 6-10.

Shell elongately ovate in outline, narrowly perforate, having an acutely elevated spire and moderately inflated body whorl, descending at the aperture. The spire is higher than the body whorl. Whorls rapidly increasing in size, coiling below the periphery, gently convex and appearing to be smooth on the

surface. Suture well impressed. Aperture pyriform in outline, slightly produced at the base.

Altitude of shell	12.0	11.0
Width of shell	7.2	6.0
Height of aperture	6.0	5.4
Width of aperture	4.5	4.0
Number of whorls	6.0	5.0

The species resembles *Triasamnicola latispira* Yen and Reeside (1946), but it differs by its more acutely conical and higher spire and broader body whorl, which produces an assiminoid rather bithynoid outline of the shell.

Holotype: Mus. N. Arizona G2-4033; Paratypes: Mus. N. Arizona G2-4032, 4037, 4039, 4040, 4043.

Horizon and locality: 48′ 6″ below the Chinle-Wingate? contact in cherty limestone, about 28.7 miles south from Navajo Bridge on U. S. highway 89, north of Tuba City, Arizona.

Triasamnicola sp. undet.
Plate 1, figs. 11-12.

Two imperfectly preserved specimens seem to represent young forms of an indeterminable species. The spire is smaller than the body whorl and the whorls coil along the periphery rather than below it.

Figured specimens: Mus. N. Arizona G2-4049 and 4051; Horizon and locality: same as the preceding species.

Lioplacodes canaliculatus Yen, n. sp.
Plate 1, figs. 13-19.

Shell ovately oblong in outline, having a highly turrited spire and narrowly inflated, descending body whorl. The spire is higher than the body whorl. Whorls increasing rapidly in size, coiling below the periphery, strongly and roundly convex, distinctly but narrowly excavated below the suture to form an angulate shoulder on the whorl. Aperture appearing to be pyriform in outline; peristomal margin thin, angulated at upper part of outer lip in conformity with the distinct shoulder of the whorl. Umbilicus narrow but definitely open.

Altitude of shell	16.0	11.0
Width of shell	10.5	7.0
Height of aperture	9.0	5.0
Width of aperture	- -	- -
Number of whorls	5.0	4.0

The species differs from *Lioplacodes veternus* (Meek) by its roundly convex whorls with an excavation below the suture, and its open umbilicus. The generic assignment of this Triassic species is provisional, though it may belong to a group closely related to *Lioplacodes* Meek, species of which have been recorded from late Jurassic to early Tertiary times.

Holotype: Mus. N. Arizona G2-4036; Paratypes: Mus. N. Arizona G2-4034, 4041, 4042, 4045, 4046.

Horizon and locality: 48′ 6″ below the Chinle-Wingate? contact in cherty limestone, about 28.7 miles south from Navajo Bridge on U. S. highway 89, north of Tuba City, Arizona.

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PREPARATION OF LARGE SIZE THIN SECTIONS

ANDREW J. LANG, JR. and HARRY W. SMEDES

ABSTRACT. A description of the apparatus for and the technique of making lantern-slide size thin sections is presented. Special precautions are emphasized in the hope that by observing them other workers will be able to duplicate the writers' results.

INTRODUCTION

TO the writers' knowledge, the first attempt to prepare large 3¼ x 4 inch thin sections was that of Arthur W. Schmidt at the University of Washington in 1941. Schmidt has subsequently prepared and used large sections in connection with his work with the U. S. Army Engineers.

Dr. V. C. Clauson, also of the University of Washington, and Mr. L. B. Jensen, preparator for the geology department, developed improved techniques which enabled them to make large size sections of standard thickness. Through their cooperation, the present writers were enabled to duplicate their results.

Many rock specimens show features of such scale that standard size sections are inadequate and often misleading. On the other hand, the magnitude of these features does not always warrant the preparation of sections of lantern-slide size. To satisfy such a size requirement, 2 x 2 inch slides are used. Since they are intermediate in size between standard and large thin sections, and since the same techniques are used in making them, it is considered advisable to attempt this 2 x 2 inch size first.

A successful technique depends principally upon the observance of certain precautions. Clauson recognized these and the present writers wish to emphasize them as each step of the procedure is described.

GRINDING APPARATUS

Two laps are used, one for preliminary grinding, and the other for final grinding. A simplified drawing of the construction is shown in figure 1. Only the overall dimensions are given; the details can be varied according to the individual.

The most important single variation from standard grinding apparatus is the variable-speed friction-drive constructed

by Mr. L. B. Jensen. When the operator's body presses against the "speed-control" board, the motor base pivots, causing the small friction drive cylinder on the motor to contact the large main drive wheel whose axle is also that of the lap wheel. By pushing gently on this board the lap will rotate slowly due to slight contact of drive wheels, and also to frictional drag created by pressure of the section being ground. The rim of the wooden main drive wheel is surfaced with rubber to increase friction. By applying increasing pressure to the control board, speeds up to 175 rpm may be attained. It should be mentioned

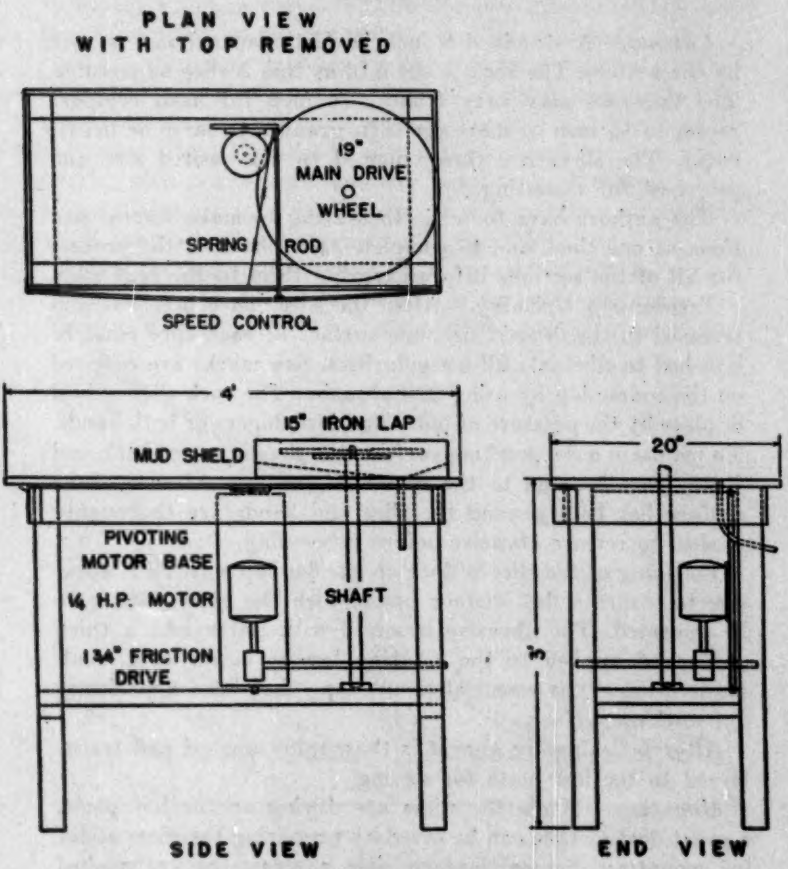

Fig. 1. Grinding apparatus

that at very low speeds the lap may have a tendency to pluck mineral grains from rather poorly consolidated rock slices.

The grinding laps are made of 15 x ½ inch boiler plate. a 4 x ⅛ inch well is ground at the center of the lap to aid in keeping the surface of the lap flat. The base of the main drive shaft is mounted in a socket lined with roller bearings, as is the upper part of the shaft at table-top height. Welded onto the top of the shaft is an 8 inch metal disc upon which the lap rests.

TECHNIQUE

Cutting.—A standard 8 inch Di-Met diamond saw is used by the writers. The rock is cut into as thin a slice as possible. The thickness may vary from 1/16 inch for hard compact rocks, to ⅛ inch or more for soft, granular, coarse or brittle rocks. The slices are then trimmed to the desired size and prepared for mounting.

The authors have found it timesaving to make several sections at one time, and to complete each phase of the process for all of the sections before carrying them to the next step.

Preliminary Grinding.—After the slices have been cut and trimmed to the desired size, one surface of each slice must be polished to eliminate all irregularities. Saw marks are removed on the coarse lap by using 220 abrasive. The rock slice is held in place by the pressure of index and fore-fingers of both hands. To maintain a flat working surface, the slice is moved back and forth from the rim to the center of the lap. After a plane surface has been ground the slice and hands are thoroughly washed to remove abrasive before proceeding.

Polishing of the slice is done on the fine lap with FFF abrasive to insure a flat surface upon which the glass slide is to be cemented. The abrasive is mixed with water into a thick paste and applied to the rotating lap by means of a small paint brush. It is essential to use laps that have a perfectly flat working surface.

After polishing the slice it is thoroughly washed and transferred to the hot plate for drying.

Mounting.—While the slices are drying on the hot plate, a great deal of time can be saved by preparing the glass slides for mounting. Several lantern slide coverglasses are washed with liquid soap and water to remove grease and lint and are

then thoroughly rinsed with hot water to remove all soap film.

To facilitate drying the glasses a simple rack can be made by cutting parallel grooves (ca. ⅛ inch deep) across a long narrow strip of plate glass. The glass slides are then placed in the grooves and the rack can be placed near the hot plate to hasten drying (fig. 2).

A piece of plate glass placed over the entire heating surface of the hot plate insures a flat working surface for more perfect contact between rock slice and glass slide during mounting.

After the glass slides are dry, all dust and lint is removed by wiping with lens tissue or other suitable material. They are then placed flat on the hot plate and allowed to heat.

For a mounting medium the writers have found Lakeside #70 Transparent Cement a very satisfactory material. It is manufactured in stick form and is therefore easier to apply and store than Canada balsam. It also requires less rigid heating time-temperature controls, and has a refractive index and dispersion similar to Balsam. It is necessary to maintain a constant hot plate temperature of ca. 145°C.

After the rock slices have been thoroughly dried (a period of 20 minutes or more) the cement is spread evenly over the polished surface of the slice and over the heated glass slides.

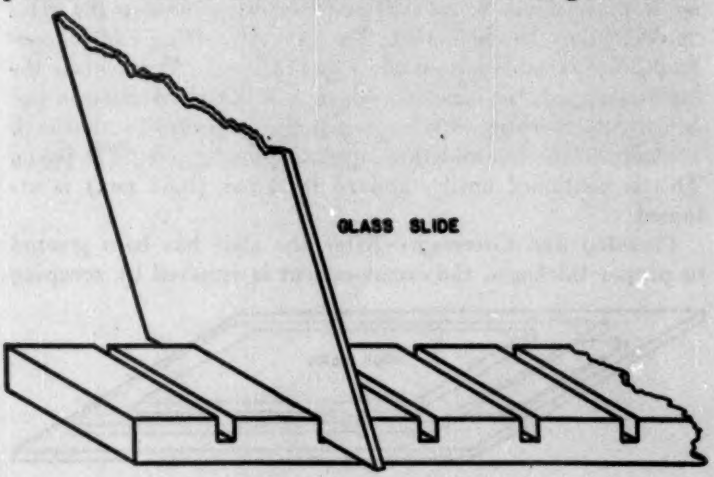

Fig. 2. Slide drying rack

A slide is then inverted and placed at a tilt upon one edge of a rock slice and allowed to drop slowly in order to remove all air bubbles by forcing them outward. Any remaining bubbles may be removed by applying pressure with a pencil or similar object to force the bubbles outward. By inverting the slide in this manner rather than the rock slice, it is possible to see that all bubbles are removed. The mounted slices are then removed from the hot plate and permitted to harden, after which they are ready for the final grinding.

Final Grinding.—Most of the thickness is removed by using coarse abrasive (No. 90). This may be replenished from time to time and if necessary the old abrasive can be removed by washing. Grinding is continued until the slice is about 1 mm thick, at which time the lap, slice, and hands are thoroughly washed.

The above procedure is repeated by using 120 abrasive until the slice is about 0.5 mm thick, and then on 220 until the inherent colors of the minerals are visible. After thorough washing the slice is ready for the fine lap.

Again a paste of FFF is applied to the lap. Great care must be taken to exert a uniform pressure over the entire slice. This can most easily be done by using a plate glass "holder" as shown in figure 3. As skill and confidence develop the glass "holder" may be eliminated. The rate of cutting can be controlled by variable lap speeds (25-175 rpm). At intervals the lap is stopped, the slice is washed, and examined under a polarizing microscope. Further grinding is preceded by thorough washing of the lap and then application of fresh FFF paste. This is continued until standard thickness (0.03 mm) is attained.

Cleaning and Covering.—After the slide has been ground to proper thickness, the excess cement is removed by scraping

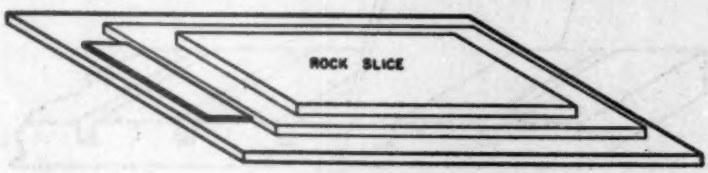

Fig. 3. Thin section "holder"

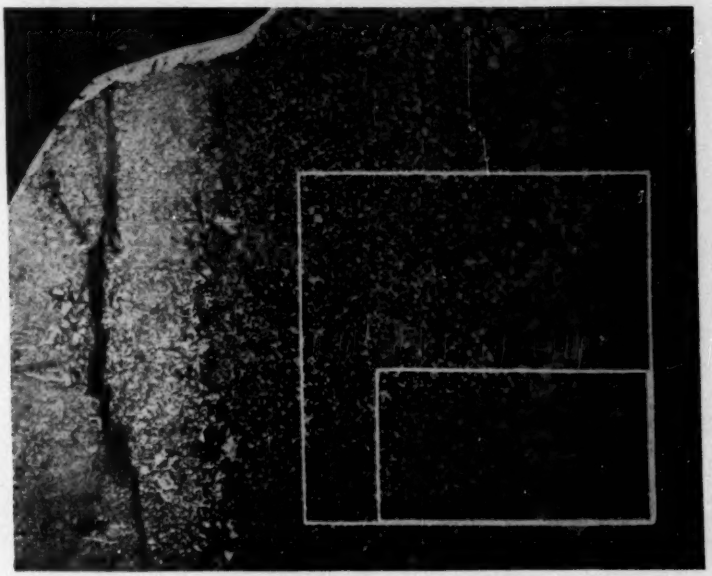

Plate 1. Photograph of 3¼x4 inch thin section with outlines showing relative sizes of 2x2 inch and 22x40 mm sections.

with a razor blade. Thorough washing with soap and water and then thorough rinsing will remove all particles of abrasive. When the cleaned slides are dry they are covered with clean dry cover glasses. Ordinary lantern slide cover glasses 1 mm thick are satisfactory unless the use of high-power short-focus objectives is contemplated, in which case special thin cover glasses should be used. The writers have found Permount a good substitute for Canada balsam as a cementing medium.

The covered slides should be put away flat for at least two days to allow the Permount to harden, after which time the excess cement can be scraped off with a razor blade and the slide washed with soap and cold water. The sections can now be bound with slide binding tape and are ready for use.

Precautions.—

1. During all grinding operations both laps must be kept perfectly flat.
2. The rock slice must have a smooth flat surface and be thoroughly dried before mounting.
3. It is especially important, when changing to a finer abrasive, that the grinding apparatus, rock slice and hands be thoroughly washed to remove all previously used abrasive.
4. Uniform pressure must be applied to the entire surface of the slice while grinding.
5. The fine lap must be washed before each application of fresh FFF paste.
6. The importance of thorough cleanliness throughout the grinding room cannot be over-emphasized.

Applications.—Many standard size sections are required to accomplish the work of one large section, but they fail in that they do not readily integrate the whole picture for the observer. This is easily done in the large sections where the different portions of the rock are spatially oriented.

Whenever the detail in the rock sample does not warrant the preparation of sections of lantern slide size and yet cannot be adequately covered on a standard size section, 2 x 2 inch slides may prove satisfactory. In plate 1 the advantages of large sections over those of standard size are readily seen. It is apparent, moreover, that standard size sections are ample when dealing with homogeneous rock material. Both of these

large sizes (3¼ x 4 inch and 2 x 2 inch) can be used in standard lantern slide projectors; the 2 x 2 inch size will also fit 35 mm projectors.

These large thin sections have wide applications. Goodspeed (1948) and other members of the Geology Department at the University of Washington, Seattle, use large thin sections for research, classroom demonstration, lecture illustration, and the presentation of scientific papers.

A projector can be adapted for polarized light by placing a strip of sheet polaroid on each side of the thin section. The projector thus becomes a polarizing microscope. Also, large thin sections may be studied under a wide-field binocular microscope converted for use with polarized light by using two sheets of polaroid, one below the stage, and the other suspended beneath the objectives and above the section.

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CHANGE OF FREE ENERGY WITH PRESSURE OF THE REACTION NEPHELINE + ALBITE = 2 JADEITE

H. S. YODER AND C. E. WEIR

ABSTRACT. The change of free energy with pressure for the reaction nepheline + albite = 2 jadeite was computed from values of the density and compressibility determined by the writers and the unpublished thermal expansion data of Rosenholtz and Smith and was found to be very small.

INTRODUCTION

DIRECT experimental determination of the stability relations of jadeite has not been successful (Yoder, 1950), and for this reason the indirect thermodynamic approach has been adopted. By determining the thermodynamic properties of the phases in the assumed reaction:

$$\underset{\text{(albite)}}{NaAlSi_3O_8} + \underset{\text{(nepheline)}}{NaAlSiO_4} = 2\ \underset{\text{(jadeite)}}{NaAl(SiO_3)_2}$$

the pressure and temperature conditions under which this reaction may go can be computed. The following provisional thermodynamic values at a pressure of 1 atmosphere have been determined for the assumed reaction:

$\Delta S^\circ_{298.16} = -14.7$ cal/mol — Kelley (personal communication, 1949),

$\Delta H^\circ_{298.16} = -6700$ cal/mol — Kracek and Neuvonen (personal communication, 1950),

where S is the entropy and H the enthalpy. Since the change in free energy $\Delta F = \Delta H - T\Delta S$, the value of $\Delta F^\circ_{298.16}$ for the reaction is negative, and therefore jadeite is the more stable phase at room temperature and atmospheric pressure. When the high-temperature specific heats are known it will be possible to calculate the change in free energy, ΔF, for the assumed reaction at all temperatures at a pressure of 1 atmosphere.[1] Values of the free energy change for the assumed reaction at higher pressures can be calculated from the corresponding values at atmospheric pressure by the relation

$$\frac{\partial (\Delta F)}{\partial P} = \Delta V,$$

[1] The high-temperature specific heats of albite have been measured (White, 1919); it is anticipated that F. C. Kracek will determine the high-temperature specific heats of nepheline and jadeite at a later date.

where P is the pressure and V the volume. Using the densities, thermal expansions, and compressibilities of each phase, ΔV can be evaluated for the reaction as a function of both temperature and pressure. It is the purpose of this paper to report ΔV and $\frac{\partial (\Delta F)}{\partial P}$ for the assumed reaction, using the values of density and compressibility determined by the writers and the unpublished linear thermal expansion data of Rosenholtz and Smith (personal communication, 1950).

THERMAL EXPANSION

The linear thermal expansion data, kindly supplied by J. L. Rosenholtz and D. T. Smith of Rensselaer Polytechnic Institute, are given in table 1. The volume thermal expansion for albite (triclinic) was taken as the sum of the linear thermal expansions in the three axial directions; for jadeite (monoclinic), the sum of the linear thermal expansions in three orthogonal directions in a polycomponent specimen; for nepheline (hexagonal ?), the sum of the linear thermal expansions

TABLE 1

Thermal Expansion Data of Rosenholtz and Smith (unpublished)

Phase (Source)	$\alpha \times 10^6$ orientation	Interval of Temperature—from 20°C to 100	200	300	400	500	600	700	800
Albite (Amelia County, Va.)	∥a	11.52	12.03	12.68	13.24	13.61	14.12	14.32	14.68
	∥b	4.68	5.02	5.57	6.04	6.36	6.80	7.35	7.72
	∥c	0.71	1.47	2.65	3.63	4.43	5.16	5.88	6.68
	α_v (obs)	16.91	18.52	20.90	22.91	24.40	26.08	27.55	29.08
	α_v (calc)	16.76	18.85	20.88	22.70	24.45	26.09	27.62	29.04
Nepheline (Gooderham Ont., Canada)	∥c	9.11	10.96	11.83	13.09	14.48	15.67	16.02	15.91
	⊥c	13.37	15.44	16.92	17.97	19.34	20.29	20.95	21.47
	α_v (obs)	35.85	41.84	45.67	49.03	53.16	56.25	57.92	58.85
	α_v (calc)	36.03	41.26	45.94	49.78	53.08	55.73	57.74	59.10
Jadeite (Burma, USNM 94829)	A	7.75	8.24	8.62	8.97	9.06	9.53	10.01	——
	B	6.55	7.13	7.57	7.92	8.25	8.74	9.26	——
	C	6.37	6.89	7.29	7.58	7.85	8.34	8.82	——
	α_v (obs)*	20.67	22.26	23.48	24.47	25.16	26.61	28.09	——
	α_v (calc)	20.89	22.06	23.23	24.39	25.56	26.72	27.89	——

*A distinct small change beginning at 510° and ending at 525° was exhibited by all specimens. The coefficient of volume thermal expansion in this temperature range has a value of 41.19 x 10^{-6}; this change was neglected in the calculations. Only values up to 700° need be considered since jadeite melts metastably at a temperature at least as low as 800° after long heating.

parallel to c plus twice that perpendicular to the c axis.[2] The volume thermal expansions, α_v, are expressed in terms of the following equations obtained by the method of least squares:

$$\alpha_{Ab} = 15.00 \times 10^{-6} + 2.240 \times 10^{-8}(t\text{-}20) - 5.65 \times 10^{-12}(t\text{-}20)^2$$
$$\alpha_{Ne} = 31.39 \times 10^{-6} + 6.063 \times 10^{-8}(t\text{-}20) - 32.17 \times 10^{-12}(t\text{-}20)^2$$
$$\alpha_{Jd} = 19.96 \times 10^{-6} + 1.166 \times 10^{-8}(t\text{-}20),$$

where t is temperature in °C and α_{Ab} is the coefficient of volume thermal expansion of albite. The numerical constants in the above equations, as well as those following, are carried out to the number of figures indicated only for internal consistency.

Since $V = V_o(1 + \alpha t)$ the volume at any temperature at 1 atmosphere can be obtained. The molal volumes of the phases can be computed from the measured densities of the specimens used and their theoretical molecular weights:

Phase	Density 20° C	Mol Wt.	Molal Vol.
Albite (Amelia, Va.)	2.605	262.15	100.633
Nepheline (Gooderham, Ont.)	2.616	142.08	54.293
Jadeite (Burma)	3.328	202.09	60.724

The molal volume of each phase at temperatures between 293° and 973° K and at a pressure of 1 atmosphere can be found by the equations:

$$V_{Ab} = 100.399 + 0.42 \times 10^{-4}T + 2.754 \times 10^{-6}T^2 - 5.68 \times 10^{-10}T^3$$
$$V_{Ne} = 54.120 - 6.75 \times 10^{-4}T + 4.827 \times 10^{-6}T^2 - 17.47 \times 10^{-10}T^3$$
$$V_{Jd} = 60.430 + 7.97 \times 10^{-4}T + 0.708 \times 10^{-6}T^2,$$

where T is the temperature in °K and V is the molal volume in cc/mol.

COMPRESSIBILITY

The apparatus and experimental method for obtaining the compressibilities of the phases have been described previously (Weir, 1950). The equipment and methods were designed to conform closely to those used successfully by workers at the Geophysical Laboratory. The present apparatus differs only in slight modifications of the pressure vessel and accessories and in that the shunted-decade type Wheatstone bridge was used to measure the resistance of the manganin pressure gage.

An experiment consists of determining the pressure and the corresponding displacement of a leak-proof piston (Bridg-

[2] The volume thermal expansions obtained in the manners described for albite and jadeite are approximations; for discussion see Wooster (1938, 25-27).

man, 1914) which is forced into a pressure vessel containing the specimen immersed in varsol. A similar experiment performed with a steel bar of nearly equivalent volume permits the calculation of the compressibility of an unknown material in terms of the steel bar whose compressibility is known (Bridgman, 1940, 1949). Equations for this calculation have been outlined by Adams, Williamson, and Johnston (1919).

The materials investigated are described below.

Albite. Varuträsk, Sweden. Collected by Th. G. Sahama. Contains less than 3 per cent impurities. Density at 25.6° C = 2.641. An analysis of the purified material by E. G. Zies shows:

SiO_2	68.76	MgO	0.00
Al_2O_3	19.50	Na_2O	11.51
Fe_2O_3	0.13	K_2O	0.13
TiO_2	0.00	P_2O_5	0.02
CaO	0.13	H_2O	0.08
		Total	100.26

The thermal expansion data on this material were considered unsatisfactory by Rosenholtz because of the presence of a significant amount of quartz and because of residual strains within the deformed material. Unfortunately the albite from Amelia County, Virginia, was not suitable for the compressibility experiments.

Oligoclase. Same cylinder used by Adams and Williamson (1923). No chemical analysis was made; the optical properties indicate An_{22}. On the basis of X-ray evidence, O. F. Tuttle gives An_{23}.

Burmese Jadeite. Same cylinder used by Adams and Gibson (1929). USNM 94829. On microscopic examination, H. E. Merwin found the material to be practically pure jadeite. An analysis by E. G. Zies has been published recently (Yoder, 1950, p. 229). The material used for the thermal expansion work was cut from the same hand specimen.

Japanese Jadeite. Cylinders were cut from a specimen from Kotaki, Japan. USNM 105860. Microscopic examination revealed considerable analcite. An analysis by O. von Knorring will soon be published by F. C. Kracek and K. J. Neuvonen. Analyses of similar material are given by Kawano (1939). Density at 24.2° C = 3.189.

Nepheline. Collected by J. F. Schairer 1.5 miles southeast of Gooderham, Ontario, Canada. Cut from the same crystal used in the thermal expansion experiments. Microscopic examination indicated the material to be virtually free of impurities. An analysis of selected material by E. G. Zies shows:

SiO_2	43.60	Na_2O	15.82
Al_2O_3	34.02	Li_2O	0.01[2]
Fe_2O_3	0.10	K_2O	5.47
TiO_2	trace[1]	MnO	trace[1]
CaO	0.75	Ign (850° C)	0.16
MgO	0.04		
		Total	99.97

[1]Present but in amounts less than 0.01 per cent.

[2]Lithium is definitely present and the amount is about 0.01 per cent.

The high potash content may affect the compressibility and expansivity. However, from what is known about the relative behavior of soda and potash compounds (for example, albite and orthoclase), the potash-bearing nepheline used in the measurements probably gives results close to those to be expected from pure soda nepheline. The small amount of lime and the excess silica probably do not influence measurably the result.

The results of the individual measurements of decrease in volume are given in table 2 and the average values are shown graphically in figure 1. The relation of the values for the feldspars to other members of the plagioclase series is presented in figure 2.

Data obtained under two slightly different experimental conditions are recorded separately in table 2. Determinations were made with the micrometer dial gage, used to measure piston displacement, mounted on the upper (movable) platen of the hydraulic press. This method of mounting appeared to introduce noticeable irregularities in the measurements of the highly incompressible jadeite. More reproducible results for these materials were obtained with the dial gage mounted directly on the ram actuating the leak-proof piston. Data obtained with the latter arrangement were assigned double weight in calculating the average $-\frac{\Delta V}{V_o}$.

TABLE 2

Results of Compressibility Measurements

Burmese Jadeite

$V_o = 20.097$cc $a = 0.198 \times 10^{-3}$ $b = 0.747 \times 10^{-6}$ $c = 0.21 \times 10^{-11}$

P atm	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Av Exptl	$-\frac{\Delta V}{V_o}$, Calc
10,000	0.00620	0.00633	0.00627	0.00630
9000	552	567	560	553
8000	457	471	464	476
7000	398	408	403	398
6000	319	333	326	322
5000	250	249	250	246
4000	171	169	170	170
3000	91	89	90	95
2000	00	00	00	−0.00020
1000	−0.00087	−0.00102	−0.00095	

Japanese Jadeite

$V_o = 20.167$cc $a = 0.382 \times 10^{-3}$ $b = 1.11 \times 10^{-6}$ $c = -1.5 \times 10^{-11}$

P atm	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Av Exptl	$-\frac{\Delta V}{V_o}$, Calc
10,000	0.00855	0.00814	0.00835	0.00828
9000	755	720	738	744
8000	668	643	656	652
7000	558	546	552	556
6000	455	465	460	459
5000	362	361	362	358
4000	258	258	258	255
3000	142	148	145	147
2000	000	000	000	−0.00038
1000	—	−0.00112	−0.00112	

Swedish Albite

$V_o = 20.122$cc $a = 0.04 \times 10^{-3}$ $b = 2.02 \times 10^{-6}$ $c = -2.16 \times 10^{-11}$

P atm	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Exptl[1]	$-\frac{\Delta V}{V_o}$, Av Exptl	$-\frac{\Delta V}{V_o}$, Calc
10,000	0.01504	0.01472	0.01488	0.01481
9000	1327	1301	1314	1310
8000	1161	1131	1146	1136
7000	978	952	965	960
6000	801	765	783	777
5000	599	581	590	591
4000	406	391	398	397
3000	209	206	208	202
2000	000	000	000	−0.00004

Nepheline

$V_0 = 19.812$cc $\quad a = 0.26 \times 10^{-4}$ $\quad b = 2.05 \times 10^{-6}$ $\quad c = -0.52 \times 10^{-11}$

P atm	$-\frac{\Delta V}{V_0}$, Exptl[1]	$-\frac{\Delta V}{V_0}$, Exptl[2]	$-\frac{\Delta V}{V_0}$, Exptl[2]	$-\frac{\Delta V}{V_0}$, Av Exptl	$-\frac{\Delta V}{V_0}$, Calc
10,000	0.01640	0.01640	0.01613	0.01638	0.01633
9000	1452	1432	1420	1439	1436
8000	1254	1214	1232	1238	1237
7000	1041	1033	1005	1030	1038
6000	844	844	861	848	838
5000	640	629	667	644	636
4000	430	417	456	433	434
3000	223	222	253	230	230
2000	000	000	000	000	−0.00026
1000	−0.00232	—	—	−0.00232	

Oligoclase

$V_0 = 20.124$cc $\quad a = 0.004 \times 10^{-3}$ $\quad b = 1.79 \times 10^{-6}$ $\quad c = -1.34 \times 10^{-11}$

P atm	$-\frac{\Delta V}{V_0}$, Exptl[1]	$-\frac{\Delta V}{V_0}$, Exptl[2]	$-\frac{\Delta V}{V_0}$, Exptl[2]	$-\frac{\Delta V}{V_0}$, Av Exptl	$-\frac{\Delta V}{V_0}$, Calc
10,000	0.01342	0.01296	0.01396	0.01344	0.01344
9000	1210	1147	1227	1199	1186
8000	998	1007	1038	1010	1024
7000	861	856	883	865	861
6000	697	678	729	701	695
5000	535	519	508	524	525
4000	361	349	329	350	353
3000	184	179	165	178	178
2000	000	000	000	000	000
1000	−0.00186	—	—	−0.00186	

[1] Observations with dial gage mounted directly on ram.
[2] Observations with dial gage mounted on platen of press.

Three measurements of relative volume change are reported for oligoclase and nepheline while two measurements are reported for each of the jadeite specimens and the Swedish albite. The relative volume change, $-\frac{\Delta V}{V_0}$, is equal to $\frac{V_{2000} - V_P}{V_0}$ where V_0 is the volume at atmospheric pressure, V_P is the volume at the pressure P, and V_{2000} is the volume at 2000 atmospheres. Average values of the volume change were obtained by weighting the values as described above. The average experimental values shown in table 2 are well represented by the equation:

$$-\frac{\Delta V}{V_0} = a + b(P\text{-}2000) + c(P\text{-}2000)^2.$$

This equation was fitted to the data by the method of least squares and the values of the constants a, b, and c so obtained are recorded in table 2. Values of the decrease in volume calculated by means of the equation are recorded for each pressure and may be compared with the average experimental values. The data for Burmese jadeite and oligoclase agree well with the experimental data previously reported (Adams and Gibson, 1929; Adams and Williamson, 1923) on the same specimens if it is noted that the earlier values are in terms of megabaryes, which at the time those papers were written was the name given to the pressure unit now called the bar.

The value of the compressibility β, equal to $-\frac{1}{V_o}\frac{dV}{dP}$, may be obtained by differentiating the above equation:

$$\beta = b - 4000c + 2cP.$$

In order to obtain the value of the specific molal volume change, the compressibility expression is integrated between the limits of $P_o = 0$ and $P_1 = P$:

$$\Delta V = -V_o\,[(b\text{-}4000c)P + cP^2].$$

This procedure involves the assumption that the expression

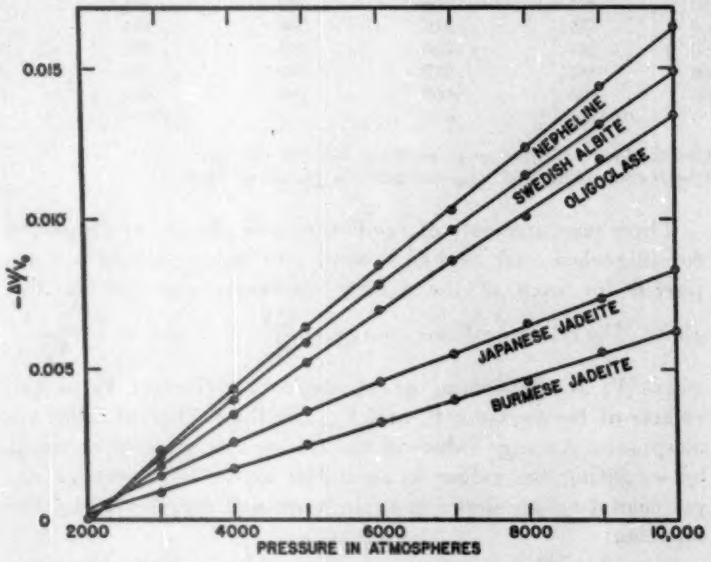

Figure 1. Relative volume change as a function of pressure for selected natural minerals.

for β, which was experimentally determined between the limits of 2000 and 10,000 atmospheres, is valid in the region of 0 to 2000 atmospheres.

Assuming that the temperature coefficient of the compressibility is negligible, the change in molal volume of the phases in the assumed reaction at $T = 298°$ K and for pressures between 0 and 10,000 atmospheres is given by the following equations:

$$\Delta V_{Ab} = -2.128 \times 10^{-4}P + 2.17 \times 10^{-9}P^2 \text{ cc/mol}$$
$$\Delta V_{Ne} = -1.113 \times 10^{-4}P + 0.28 \times 10^{-9}P^2 \text{ cc/mol}$$
$$\Delta V_{Jd} = -0.449 \times 10^{-4}P - 0.18 \times 10^{-9}P^2 \text{ cc/mol}$$

where the subscript Ab refers to the data for the Swedish albite; Ne, nepheline; and Jd, Burmese jadeite.

It is to be noted that the sign of the coefficient of the P^2 term for ΔV_{Jd} is negative. It is, however, unlikely that the rate at which the volume decreases would increase with pressure. The negative value is merely indicative of the experimental error and indicates that for materials of low compressibility the piston displacement method is not capable of detecting small changes in the compressibility.

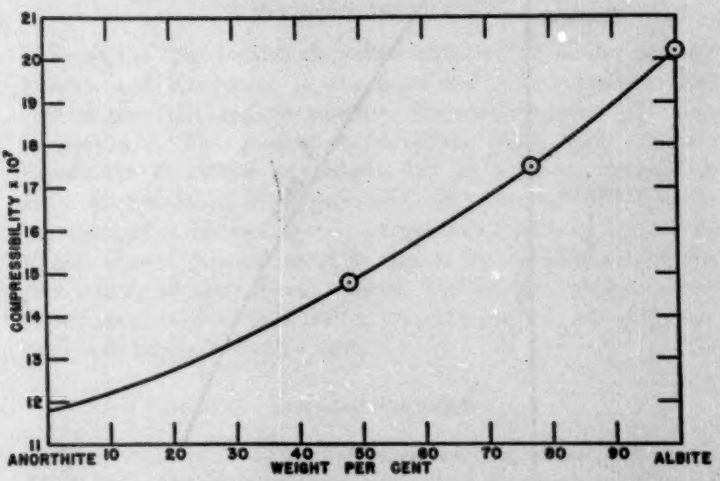

Fig. 2. Compressibility of plagioclase feldspars. Points are based on an average of new data and the data of Adams and Gibson (1929) and Adams and Williamson (1923).

RESULTS OF COMPUTATIONS

By combining the results of the thermal expansion and compressibility experiments, the molal volumes of each phase as a function of pressure, P, in atmospheres and temperature, T, in °K are:

$$V_{Ab} = 100.399 + 0.42 \times 10^{-4}T + 2.754 \times 10^{-6}T^2 - 5.68 \times 10^{-10}T^3 - 2.123 \times 10^{-4}P + 2.17 \times 10^{-9}P^2 \text{ cc/mol}$$

$$V_{Ne} = 54.120 - 6.75 \times 10^{-4}T + 4.827 \times 10^{-6}T^2 - 17.47 \times 10^{-10}T^3 - 1.11 \times 10^{-4}P + 0.28 \times 10^{-9}P^2 \text{ cc/mol}$$

$$V_{Jd} = 60.430 + 7.97 \times 10^{-4}T + 0.708 \times 10^{-6}T^2 - 0.449 \times 10^{-4}P - 0.13 \times 10^{-9}P^2 \text{ cc/mol.}$$

The change in volume for the assumed reaction is given by $\Delta V = 2V_{Jd} - (V_{Ab} + V_{Ne})$. The expression of the volume change of the assumed reaction is:

$$\Delta V = -33.660 + 22.27 \times 10^{-4}T - 6.166 \times 10^{-6}T^2 + 23.15 \times 10^{-10}T^3 + 2.339 \times 10^{-4}P - 2.71 \times 10^{-9}P^2 \text{ cc/mol,}$$

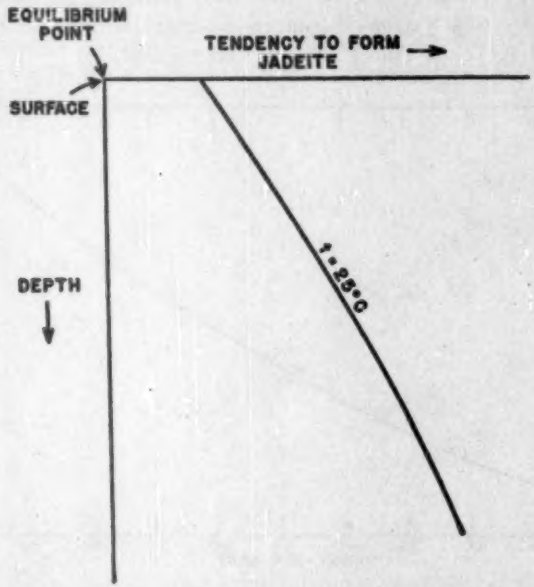

Fig. 3. Schematic diagram indicating the tendency to form jadeite ($-\Delta F$) from the reaction nepheline + albite → 2 jadeite as a function of depth in the earth (P).

and the change of free energy with pressure is:

$$\frac{\partial(\Delta F)}{\partial P} = -0.8148 + 0.589 \times 10^{-4}T - 0.1492 \times 10^{-6}T^2 + 0.560 \times 10^{-10}T^3 + 0.0566 \times 10^{-4}P - 0.066 \times 10^{-8}P^2,$$

with ΔF in calories per mol, P in atmospheres, and T in °K.

In order to illustrate the magnitude of the volume term and the change of free energy with pressure, the numerical calculations have been made for the extremes of temperature and pressure:

P atm.	T °K	ΔV cc/mol	$\frac{\partial(\Delta F)}{\partial P}$
1	298	−33.478	−0.8104
1	973	−35.261	−0.8520
10,000	298	−31.411	−0.7603
10,000	973	−33.193	−0.8020

The effect of pressure on the change of free energy is evidently very small for the assumed reaction.

GEOLOGICAL IMPLICATION

From the thermodynamic values obtained by Kelley and by Kracek and Neuvonen, it can be stated with certainty that jadeite does not require pressure for its formation at room temperature. The present calculations show that pressure *favors* the formation of jadeite, but at a slowly decreasing rate. Stated in another way, the tendency to form jadeite increases at a decreasing rate at greater depths in the earth; this is shown schematically in figure 3. No estimate of the free energy of activation required, that is, the energy barrier which must be overcome before the reaction will actually proceed, can be made at this time.

ACKNOWLEDGMENT

The writers wish to acknowledge the role played by Dr. L. H. Adams, Director of the Geophysical Laboratory, through whose persuasion over a period of years much of the data on the minerals described were obtained by the various investigators.

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COMMUNICATION

TREE TRUNKS PRESERVED IN LAVA

A propos the article by Herbert P. T. Hyde in a recent number of your Journal (1951), describing tree trunks preserved in lava in the Cameroons, I should like to direct the attention of your readers to several descriptions of phenomena, similar but perhaps even more remarkable, from New Zealand, published by the late Professor J. A. Bartrum (1925, 1941, 1946).

Of these, one of the most striking is a cast in basaltic lava of part of a tree trunk that has been carbonized by the heat of the lava, with the production of radial and transverse shrinkage cracks, into which the extremely fluid lava has penetrated to form laminae often less than a millimetre in thickness. No trace of the charcoal now remains. This cast has been figured in the *Bulletin of the Hawaiian Volcano Observatory* (1925, figs. 17-19), and again in the *New Zealand Journal of Science and Technology* (1946, fig. 2)* in connection with a description of another log which has undergone the same progress, but in which much of the charcoal remains, in little blocks separated by lava laminae. Both these specimens are preserved in the Auckland War Memorial Museum.

Another phenomenon described by Professor Bartrum (1941, fig. 3) is the group of unfilled moulds of tree trunks in lava on the foreshore at Takapuna, Auckland, well known to geologists who have visited Auckland to attend scientific gatherings, which have also been illustrated in the handbook for the Auckland meeting of the Australian and New Zealand Association for the Advancement of Science in 1937.

I feel that, in considering the bearing upon the physical state of the molten rock of the effects of lava on engulfed logs, Bartrum's papers ought not to be passed over.

* The reproduction of the photographs in the first publication is better than that in the second.

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ESSAY REVIEW

Contributions to the study of depositional fabrics—Rhythmically deposited Triassic limestones and dolomites; by BRUNO SANDER, translated into English by ELEANORA BLISS KNOPF. Pp. viii, 160; 54 figs. Tulsa, 1951 (American Association of Petroleum Geologists, $4.00).—In 1936, Bruno Sander of the University of Innsbruck, Austria, published in *Tschermaks Mineralogische und Petrographische Mitteilungen* the results of a very detailed study of carbonate rocks in the Tyrol. That this article is of fundamental importance for the "dolomite problem" was evident from the first, but as the paper is written in German, and indeed in German whose admitted difficulty has been further exaggerated by rumor, it has not been widely read, and the data and the insights that it contains have not found their way into the general literature on the subject. An English translation of this paper by Mrs. E. B. Knopf, who has long been intimate with Sander's ideas, has now been published by the American Association of Petroleum Geologists, under the auspices of its Research Committee. The geological profession in the English-speaking world owes a great debt of gratitude to Mrs. Knopf for her labor on this translation and to S. W. Lowman who as chairman of the Research Committee arranged for its publication.

The 54 figures accompanying the article, mostly photographs of polished or thin sections, have been reproduced for the new translation, no mean feat as the original photographs were no longer available and it was necessary to make half-tone plates from the published half-tone reproductions. In the translation these are placed together at the end instead of being distributed through the text as in the original, whereas the bibliographic references, given in a single list in the original, have been scattered as footnotes at the appropriate places in the translation. For ready reference to the original article, the page numbers of each section in the original have been inserted after the title of that section in the translation. A new index, fuller than that in the original, has been prepared.

True accuracy in translation is proverbially difficult, and this difficulty is compounded in the present case. Mrs. Knopf quotes a witty remark by Sollas, the translator of Suess' *Das Antlitz der Erde,* on the tendency of English translations to mimic the involved structure of prose German, and she might have added remarks on the difficulty of discriminating literal from figurative meanings when both are expressed, as so often in German, by the same

word. Hence it is no reflection on the translation if the present reviewer finds passages here and there which he would have phrased in other ways, and if he suggests that those who study the work in detail refer back to the German original if the English seems unclear or inconsistent. In returning to the German text, they will find Mrs. Knopf's translation a most helpful guide.

In view of the unfamiliarity of the article, it may be in order to comment briefly on some of the principal conclusions. Perhaps the first striking result of the study is Sander's proof that these carbonate rocks consist of several genetically different components in varying proportions, any of which may be either calcite or dolomite or a mixture of the two. It follows that the problem of the origin of the dolomite resolves itself into a series of problems, one for the dolomite in each of these components. Moreover the fabric of rocks in which all the components are dolomite may be virtually identical with that of rocks in which some components are calcite, some dolomite, and some mixed, showing that the conditions that determine the presence or absence of dolomite are in considerable degree independent of the components themselves. These genetic components Sander distinguishes and characterizes by operational petrographic criteria, and his insistence on such criteria is one of the most valuable aspects of the work. Among the components some are evidently "secondary" and diagenetic, produced by "metasomatic" replacement of pre-existing carbonate rock (and either calcite or dolomite may replace either calcite or dolomite), but others are "primary," either mechanical (carbonate-mud and -sand, including organic-fragmental material), chemical (sparry crystalline carbonate, mostly in small cavities in the original fabric), or biogenic ("cheesy cavernous crusts that do not show organic patterns," p. 1*). In calling dolomite "primary," Sander means "that in early stages of rock formation dolomite came to a place in the fabric where calcite was not earlier present" (p. 123). It should be emphasized that this use of the term primary differs considerably from the conventional use in most American writings on the subject. Thus, if any particles were originally formed as calcite (organically or chemically) but were converted into dolomite on the sea floor *before* finally coming to rest in the deposit, they would be primary by Sander's definition though secondary by conventional usage, for Sander maintains that there are no observable criteria by which such so-called secondary particles could be distinguished from particles agreed to be primary by all. On the basis of this definition, primary dolomite is very important in these rocks, more so indeed than

* References in this review are to pages in the English translation.

primary calcite (and "secondary" or "metasomatic" calcite is as common as "secondary" dolomite).

At least as regards the definitely organic-fragmental part of the "primary" mechanical component, however, it would seem to the reviewer that the organic nature of the material was itself a petrographic criterion for the distinction in question. Thus the dolomitic foraminifer tests described by Sander were certainly calcite at the time of formation, even if they were dolomite at the time of burial. And if they were converted into dolomite before final deposition, why not also the indeterminate lime-mud and lime-sand in which they are embedded? It must be admitted however that no evidence that would bear on the matter one way or the other is likely to be found in the rocks themselves. Again, the strictly biogenic (presumably algal) origin of the "cheesy cavernous crusts" does not seem to be demonstrated; they may have been directly, biochemically deposited from solution at their present position, but they may also have been built up from passing carbonate-mud particles that stuck to mucilaginous jelly coating the algae; if the latter, this material too, though primary in Sander's sense, is secondary by conventional usage, though again we know no petrographic criterion for the distinction. The chemical sparry dolomite that lines and fills cavities must evidently be primary in every sense, but the water in these cavities, as Sander expressly mentions (p. 128, part of a sentence has been omitted here in translation), need not have been normal sea water; in one case however (pp. 115-116) Sander records primary chemical dolomite formed on what appears to have been the free upper surface of the deposit in contact with normal sea water, and he suggests that such material may be more widespread than yet proved. But enough has been said here to show that Sander's conclusion that "primary origin" of dolomite "predominates and is widely distributed" (p. 123) must not necessarily be interpreted as contradicting the generally accepted conclusion (based on the admittedly unsatisfactory physical-chemical data) that dolomite is not commonly precipitated directly from normal sea water.

A second important result of the study is the accumulation of evidence for repeated resedimentation of the mechanical carbonate-mud and -sand, proving that these sediments have passed through the same sort of constant working and reworking, sorting and scrambling, erosion and deposition that Barrell in his great article Rhythms and the Measuring of Geologic Time (Geol. Soc. America Bull., vol. 28, pp. 745-904, 1917) taught us to recognize in the siliceous fragmental sediments of the shallow seas. Breccias containing fragments of breccias, mechanical deposits on the floors of

small cavities in mechanical deposits, numerous closely spaced erosion surfaces—all these carefully described and analyzed features prove that the mechanical phase of the deposition of these rocks differs in no essential way from that of marine, neritic sandstone and shale, except that the source of the fragments was local and not some distant land mass. Superposed on this mechanical phase is of course the chemical phase, unique to carbonate rocks and consisting of solution and sparry recrystallization of the carbonate during diagenesis, a sort of autocementation. Sander emphasizes again and again the overlapping of these phases and of the individual processes within the phases in time, and presents a picture of a complex deposit formed by the simultaneous if locally differentiated operation of a complex group of processes. Thus Sander, largely by inductive observation, has done for the calcareous rocks what Barrell, largely by deductive reasoning, did for the siliceous fragmental rocks, and the interpretation of calcareous rocks can never again be as simple as it used to be.

A third major theme of the work, and according to Sander's foreword the main point of departure for the study, is rhythm. Most of the rocks studied consist of rhythmic alternations of massive layers a few meters thick with well laminated layers a few tenths of a meter thick, and the laminations in the latter reveal a rhythm measured in millimeters. The compositional and fabric characteristics that by varying perpendicular to the bedding produce these rhythms are carefully analyzed. Sander believes that the existence of such spatial rhythms in sedimentary rocks is evidence for time rhythms in at least some of the factors that governed the deposition of those rocks (pp. 16, 132), a conclusion that appears less secure since the publication of Kuenen and Migliorini's work on graded bedding (Jour. Geology, vol. 58, pp. 91-127, 1950). Indeed Sander compares the basic significance of rhythm in the interpretation of sedimentary rocks to the basic significance of symmetry in the interpretation of deformed rocks (tectonites) as established by his fundamental work in petrofabrics. He discusses with an open mind both epeirogenic and climatic time rhythms as possible causes of the observed spatial rhythms; while accepting the possibility that both may have operated, he suggests that the finer rhythm represents annual layering (varves) and that the coarser rhythm was produced by fluctuations in the depth of water and perhaps, from its magnitude relative to the finer rhythm, may record the 21,000 year cycle of the precession of the equinoxes. A theory of possible glacial control is considered but is shown to be not entirely in harmony with the present data.

There are many important contributions to sedimentary petrography in this work in addition to those discussed here; for exam-

ple, Sander has carefully described structures that distinguish top and bottom (for which he proposes the term "geopetal"), has proved the existence of considerable diagenetic deformation (mainly minute crumpling), has measured the degree of lattice orientation of the chemically deposited carbonate, and has indicated what a delicate balance must decide whether calcite or dolomite shall be present. The paper cannot be too highly recommended to all those interested in the carbonate rocks, both for the painstaking assembly of data it presents and for the theoretical insights it offers and stimulates. It is hoped that the new English translation will enable Sander's ideas to achieve the wide dissemination that they have from the first deserved.

JOHN RODGERS

REVIEWS

Superfluids, Vol. 1, *Macroscopic Theory of Superconductivity;* by FRITZ LONDON. Pp. viii, 161; 45 figs. New York, 1950 (John Wiley & Sons, Inc., $5.00).—Many scientists welcome as the most appealing feature of quantum mechanics its transition to classical concepts through the correspondence principle. No need to worry about the uncertainty principle or the tunnel effect—these oddities can be confined to microscopic realms, and in all macroscopic matters one can continue to apply the classical concepts so pleasing to one's intuition. This happy situation of having one's quantum mechanical cake and eating it too is regrettably illusory, as indicated especially by two macroscopic phenomena which have received much attention in recent years: the superfluidity of liquid Helium, and the superconductivity of certain metals and alloys. The most adroit manipulation of classical principles is unable to explain these effects, and so one is forced to agree with Professor London that they are indeed "quantum mechanisms of macroscopic scale." These low temperature phenomena are thus of fundamental interest from a theoretical point of view because here quantum mechanics appears on a macroscopic plane.

It is Professor London's contention that superconducting electrons and superfluid Helium atoms are in a state of long range order with respect to the value of the momentum. From the uncertainty principle there would then follow a virtual lack of constraint on the position, equivalent to an abnormally high mobility of the electrons or Helium atoms in question. At present it is not yet clear how this long range order in momentum is established, but Professor London has been able to reduce the problem of superconductivity to this basic question by showing that a set of

electrodynamic equations based on the assumed momentum order leads rigorously to a quantitative understanding of the behaviour of superconductors.

Professor London has brought together in this book in a thorough and most lucid manner the extensive work which he, partly with the collaboration of his brother, has done on this matter. After a brief statement of the properties of superconductors and their thermodynamic correlation London states the fundamental electrodynamic equations which he postulates, and from them derives relation for the behaviour of superconductors. He cites experimental evidence supporting his theory, and ends by proposing a program for a future quantum mechanical approach with which one might obtain his postulated equations from basic principles.

The book is excellently organized and written clearly and simply—a welcome contrast to many other theoretical works. It is only regrettable that Professor London has not supplemented his admirably complete theoretical treatment of superconductivity with a summary of experimental results. Even without this, however, he has made a unique contribution to low temperature physics, and all workers in the field are eagerly awaiting his promised volume on superfluidity.

E. A. LYNTON

The Life of Vertebrates; by J. Z. Young. Pp. xv, 767; 497 figs. New York and Oxford, 1950 (Oxford University Press, $8.50).—Seldom is an author bold enough to endeavor to present the chief results of such diverse subjects as biochemistry, animal behavior, and paleontology within a single volume. Those who have done so usually have not been scientists, and their attempts at synthesis generally seem inadequate to specialists in the various fields. By contrast the author of the present volume has produced a well rounded account of vertebrate biology which includes up to date information on problems currently engaging the attention of investigators in widely separated branches of science.

Professor Young maintains that study of vertebrate zoology through the separate fields of embryology, anatomy, physiology, biochemistry, paleontology, and ecology fails to give a complete picture of the life and evolution of the backboned animals. In this work emphasis is primarily historical, and topics have been selected for their bearing upon vertebrate evolution. Anatomy, physiology, and behavior of successive Classes from the protochordates to the mammals are dealt with, each followed by a summary of the classification in which fossil forms are considered together with their living relatives. Detailed description of various organ systems in the groups where they first appear permits a truly comparative

treatment in subsequent chapters. An opening chapter lays the background of the changing environmental setting through long ages of geologic time, and poses the problems of evolutionary progress and their causes. In the concluding chapter vertebrate evolution is viewed in retrospect, to see what light it throws upon the general questions of evolution. Many similarities to conclusions in G. G. Simpson's "Meaning of Evolution" are apparent here, though the philosophical implications have not been developed to such great length.

A paleontologist may object to reference to the living protochordates as "early" chordates, and feel that the echinoderm-vertebrate relationship has been overstressed. Occasional departures from currently accepted classification may be found; each of these is discussed and so related to the general picture that one is left doubting the validity of the orthodox view.

Professor Young has achieved a well balanced synthesis of paleontology and the biology of recent vertebrates which should prove extremely useful to the general zoologist and paleontologist alike. His carefully organized, well illustrated volume contains a stimulating account of the life and history of backboned animals, and provides a convenient, reliable reference. JOSEPH T. GREGORY

Symposium on Mineral Resources of the Southeastern United States: 1949 *Proceedings;* edited by FRANK G. SNYDER. Pp. x, 236; 52 illustrations. Knoxville, 1950 (University of Tennessee Press, $4.00).—This volume records the first of a series of annual symposia devoted to the economic geology of the Southeastern States and sponsored by the Universities of the Southeast and their geology departments. The 21 speakers invited to participate in the first symposium were chosen to provide discussion of a wide variety of mineral deposits, although naturally no attempt was made to exhaust all the possible subjects. The resulting volume, containing all but two of the papers originally presented, is a major contribution to our knowledge of the mineral deposits of the Southeast.

The volume opens with three general papers: on the history of development and geologic investigation (Laurence), on the tectonic setting (King), and on problems of genesis (Behre). There follow papers on specific minerals or ores: feldspar and mica (Parker), titanium in Virginia (Pegau), tungsten (Espenshade), copper at Ducktown, Tennessee (Simmons), zinc (Oder and Hook), barite (Kesler), kyanite and sillimanite (Furcron), talc, soapstone, and pyrophyllite (Stuckey), vermiculite (Hunter), brown phosphate in Tennessee (Burwell), land-pebble phosphate in Florida (Cathcart), manganese (Miser), bauxite (Bridge), economic beach sands (Cannon), and ground-water (Stringfield, DeBuchananne). Though some

of the papers are concerned only with individual districts, most of them are general and cover all important deposits of the given mineral in the region. Many of them present considerable information not previously published.

Among so many papers it is perhaps invidious to single out a few for comment, and the reviewer has no guide in this but his own interests. Simmons' paper on the Ducktown district is accompanied by a superb outcrop map of the central part of the district on a scale of 1:10,000, a model of painstaking detail in an area of very complex geology. Bridge's paper, based on the bauxite investigations of the United States Geological Survey during the last war, finally places in the published record the evidence that tends to date the Harrisburg peneplain as early instead of late Cenozoic, and will be of interest to all students of Appalachian land forms. Not the least valuable part of the book are the very full bibliographies appended to several of the papers. There is in addition a good index.

The University of Tennessee and Professor Snyder are to be congratulated on having set this high standard for the new series.

JOHN RODGERS

PUBLICATIONS RECENTLY RECEIVED

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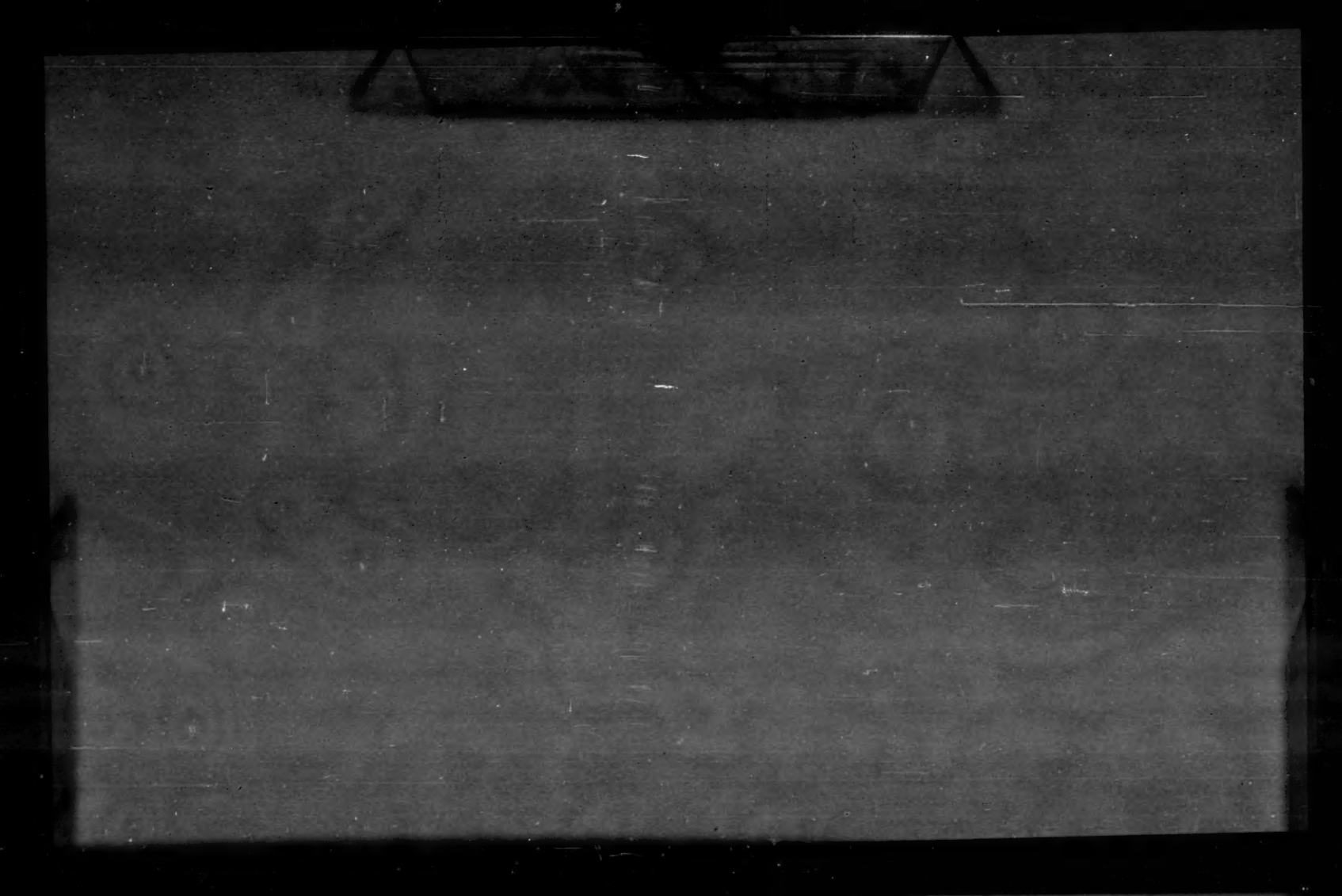

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